FINDING PERSISTENT SOURCES WITH THE BeppoSAX/WIDE FIELD CAMERA: AN IN-DEPTH ANALYSIS

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ABSTRACT

During the operational life of the Italian/Dutch X-ray satellite (1996–2002), BeppoSAX, its two Wide Field Cameras (WFCs) performed observations that covered the full sky at different epochs. Although the majority of analysis performed on BeppoSAX WFC data concentrated on the detection of transient sources, we have now applied the same techniques developed for the INTEGRAL/IBIS survey to produce the same work with the BeppoSAX WFC data. This work represents the first unbiased source list compilation produced from the overall WFC data set optimized for faint persistent source detection. This approach recovered 182 more sources compared to the previous WFC catalog reported in Verrecchia et al. The catalog contains 404 sources detected between 3 and 17 keV, 10 of which are yet to be seen by the new generation of telescopes.

Key words: catalogs – methods: data analysis – surveys – techniques: image processing – X-rays: general

Online-only material: color figures, machine-readable table

1. INTRODUCTION

The two Wide Field Cameras (WFCs; Jager et al. 1997) on board the BeppoSAX satellite (Boella et al. 1997) were mounted 180° away from each other and pointed perpendicular to the direction of the Narrow Field Instruments (NFIs), hence looking at two different sky zones during each NFI pointing. In this way, over the six years of operational life of BeppoSAX, the WFC observations covered almost all the sky with at least one pointing (typically 100 ks duration). This serendipitous observing strategy, during which the WFCs acted as secondary instruments, was driven by the approved NFI observing program. However, twice a year, for around 8% of the total observing time of the satellite, the WFCs observed the Galactic bulge region as primary instruments (thanks to a pre-planned observing program) collecting a total exposure on the Galactic center of 6 Ms during the operational life of the satellite.

The WFCs were coded mask instruments characterized by a large (40° × 40°) field of view, a good angular resolution (few arcmin), and a pointing strategy that permitted all the sky to be observed during the satellite’s operational life. The operating principles are reported in detail in Jager et al. (1997). The principal scientific objective of the WFCs on BeppoSAX was the study of the X-ray variability of the sky. In fact, through the serendipitous monitoring of large sky regions, the WFCs were able to detect a lot of transient X-ray events like gamma-ray bursts and X-ray binary (XRB) outbursts (see, e.g., Piro & Scarsi 2004 and references therein). Most of the time, the WFCs were used as triggers for follow-up studies with higher-sensitivity NFIs on BeppoSAX itself or on other platforms. The principal characteristics of the WFCs are briefly summarized in Table 1.

The goal of our study is to reanalyze the WFC data to obtain a static view of the sky averaged over all the six years of BeppoSAX’s operational life in order to search for faint persistent sources that remained hidden in previous analyses because they were too faint to be detected with an adequate confidence level in a single observation.

This work is thus complementary to the previous WFC survey analysis reported (Verrecchia et al. 2007) and it is a natural evolution of the work developed for the IBIS/INTEGRAL survey catalog (Bird et al. 2010). Indeed, the WFC principal characteristics are directly comparable with those of IBIS (Ubertini et al. 2003), the coded mask gamma-ray telescope on board the INTEGRAL satellite (Winkler et al. 2003). The aim of this paper is therefore to apply the same techniques developed for the IBIS survey (Bird et al. 2004, 2006, 2007, 2010) to the BeppoSAX WFC data, searching for faint persistent sources in the total mosaic maps made from individual WFC sky images. IBIS and the SAX WFCs have a complementary and partially overlapping energy range (3–28 keV for WFCs and 17 keV–1 MeV for IBIS), allowing studies of persistent sources over a larger energy range. Results from this work have also been used to give an independent check of some of the fainter sources detected in the IBIS survey catalog production; details of the correlation between IBIS and WFC detections can be found in Capitanio et al. (2008, 2009).

2. WFC SKY MAP PRODUCTION

The WFC data are organized into short observational periods (OPs) of at least 100 ks. We collected all the available data from different archives and analyzed all the collected OPs with the WFC Data Analysis System, extracting images in the 3–17 keV and 18–28 keV energy ranges. The data analysis up to and including the image level has been performed with the final version of the WFC standard data analysis software4 (Jager et al. 1992) using the reference catalog included in the software package.

The WFC standard software uses the IROS method (Iterative Removal of Sources) to extract sources from the shadowgrams of the WFCs coded masks (in’t Zand 1992). During this procedure we used specific parameters included in the standard software in order to keep all the detected sources in the second and subsequent IROS iterations independently of the source identification (“-m4” option within the standard software). Moreover, we lowered the IROS threshold (allowing up to 300 iterations),

4 http://www.asdc.asi.it/bepposax/software/index.html
such that the source removal continued further into the low significance detections and/or noise than would normally be done for transient detection, retaining low significance information for the mosaicing process.

We subsequently applied a filter in order to eliminate corrupted and noisy images by comparing the root mean square (rms) and mean of each flux image against the average image rms and mean level derived from all images. Any images with an rms or mean level more than 5× away from the nominal average values were not incorporated into the final mosaic. After the filtering procedure, about 95% of the total initial number of OPs were used in the subsequent analysis.

An all-sky mosaic of the images has been generated using the same software used for the IBIS survey (Bird et al. 2004, 2006, 2007, 2010). The mosaicing procedure is designed to average rms and image mean level derived from all images. Any images (rms) and mean of each flux image against the average image ruptured and noisy images by comparing the root mean square (rms) and mean of each flux image against the average image derived from all images. Any images with an rms or mean level more than 5× away from the nominal average values were not incorporated into the final mosaic. After the filtering procedure, about 95% of the total initial number of OPs were used in the subsequent analysis.

An all-sky mosaic of the images has been generated using the same software used for the IBIS survey (Bird et al. 2004, 2006, 2007, 2010). The mosaicing procedure is designed to average a large number of small single images that cover almost all the sky into a single all-sky image. Thus, the images of the filtered OPs have been combined together into all-sky mosaics. For each sky pixel, the mosaic software establishes a weighted mean flux, weighting each input image contribution according to the variance of the signal in each input pixel. The events are fully redistributed in the final sky map pixels that oversample the original image pixels and system point-spread function (PSF). The process generates flux, error, significance, and exposure mosaic images.

This procedure is strongly tuned toward the detection of persistent (and weak) sources. Even if a source field has been observed for a long time, intrinsic variability of a source may mean that it is detected only in few individual images, and it will not be detectable in the final map.

The signal-to-noise ratio ($S/N$) of a persistent source will increase with the number of added images. Conversely, noise and imaging artifacts in individual OP images that would create false detections are, by their very nature, detected in the same positions in only one image and will be lost into the mosaic background provided that two conditions are satisfied.

1. Many images must be summed together (we assume a conservative minimum value for the exposure of 1.4 Ms—at least 14 images considering that the maximum possible exposure of a single image is 100 ks). In the regions of the map with an exposure less than this value, we did not consider any detection that was not reported before in the catalog of Verrecchia et al. (2007).

2. The averaging procedure could fail to eliminate the false detections if they are due to systematic image artifacts resulting from the image reconstruction process if the sky pointing direction of the telescope is repeated. In this way, systematic effects will appear in the same sky positions and will be summed during the mosaic process. However, this is not the case of the WFC images due to their random pointings deriving from the serendipitous nature of the observing program (this kind of effect cannot be totally excluded for the Galactic center region; details are in Sections 2.1 and 4.2.1).

Moreover, the mosaic procedure, as it combines many images from many pointings, averages any differences due to the off-axis response that are not completely corrected by the software (see Verrecchia et al. 2007 for details). Also the Earth occultation simply contributes to the background of the final mosaic.

The collected data covered all the sky—although not uniformly. In fact, as Figure 1 shows, there are zones with much higher exposure such as the Galactic center and the fields centered on the north and south celestial poles due to the observing strategy and maneuvering techniques of the BeppoSAX satellite (Tramutola et al. 2000). The average exposure over the entire map is about $4 \times 10^6$ s, even if there are some regions with an exposure of two orders of magnitude less and others where the exposure reaches $2 \times 10^7$ s. There are two principal regions of low exposure: the zone around Sco X-1 (Sco X-1 was so bright that all the data containing this source in the field of view were corrupted) and two small zones of about 5° radius 180° apart at coordinates $(l, b) = (120° 2, −57° 4)$ and $(299° 0, 68° 2)$.

The higher energy range map (18–28 keV) is affected by more noise and a larger distortion of the PSF (see Section 2.1). Thus, for source searching we only use the 3–17 keV map.

It is clear that the analysis of WFC data carried out so far has concentrated on locating transient sources, whereas our methods allow a much more efficient detection of weak persistent sources. As an example, Figure 2 shows a zoom of the all-sky WFC map (3–17 keV) around GX 301–2; the sources indicated with white labels have been reported in both our and Verrecchia et al. (2007) catalogs, while the sources labeled in red are zones with a high level of noise and a larger distortion of the PSF (see Section 2.1). The three sources with yellow labels are classified as faint persistent (even if variable) sources (see, e.g., Bird et al. 2010). The flux of the sources present in Figure 2 in both catalogs is reported in Table 2.

Finally, Figure 3 shows the 3–17 keV WFC final sky map in units of $\sigma$. The symbols represent the detected source positions; the parts of the map in red are zones with a high level of noise (i.e., the Galactic and anti-Galactic center).

### 2.1. Image Problems—The “Comet” Effect and Noisy Regions

The IROS procedure performs a cross-correlation between the detector image and the mask pattern via matrix multiplication during every iteration and the detections are localized by fitting any peaks with an expected PSF. After the positions are compared with a reference catalog, the effect of sources on the detector plane is then simulated and subtracted. Because

| Parameter                      | WFC Value                  |
|-------------------------------|-----------------------------|
| Energy range                  | 3–28 keV                    |
| Energy resolution             | 20% at 6 keV                |
| Effective area                | 140 cm$^2$                  |
| Field of view                 | $40° \times 40°$ (FWZR)     |
|                                | $20° \times 20°$ (FWHM)     |
| Angular resolving power       | 5°                          |
| Source location accuracy      | $<1'$                       |
| Sensitivity in $10^3$ s       | ~1 mCrab (3–28 keV)         |

**Fluxes of Sources Shown in the Sky Field of Figure 2**

| Source Name | $F_{\text{WFC}}$ (3–17 keV) mCrab | $F_{\text{IBIS}}$ (2–10 keV) mCrab |
|-------------|-----------------------------------|-----------------------------------|
| GX 301–2    | 20.3 ± 2.1                        | 18 ± 26                           |
| 4U 1323–619 | 4.9 ± 0.5                         | 7 ± 5                             |
| IGR J12349–6434 | 0.6 ± 0.1         | ...                              |
| IGR J13020–6359 | 0.4 ± 0.1         | ...                              |
| H 1249–637 | 0.7 ± 0.1                         | ...                              |

**Notes.** $F_{\text{IBIS}}$ is the average flux extrapolated from Verrecchia et al. (2007); the large errors represent the source variability rather than an intrinsic measurement uncertainty and $F_{\text{WFC}}$ is the flux derived from the all-sky mosaic map taken from Table 3.
Figure 1. WFC mosaic exposure map (in seconds) in Galactic coordinates. The two zones with higher exposure are due to the polar passages of the Extended Science mode one (ESM1) and two (ESM2; Tramutola et al. 2000); the high exposures on the Galactic center and the anti-center zones are due to the WFC core program observations of the Galactic center region.

(A color version of this figure is available in the online journal.)

Figure 2. Zoom of the WFC final mosaic map (in units of sigma) centered around the GX 301−2 field. The sources indicated in yellow have been reported only by our catalog, while those with white labels have been reported in both our and Verrecchia et al. (2007) catalogs.

(A color version of this figure is available in the online journal.)

each source is not simulated in exactly the same position in each single OP image (in’t Zand 1992), this results in a slight broadening of the final PSF in the mosaic image.

The PSF can also be different from one single observation to the next as a result of photon penetration into the WFC detector gas chamber. This effect becomes more evident both at higher energy ranges and at large off-axis angle detections and hence can change between OPs as the pointing direction changes.

In fact, as reported in in’t Zand (1992), the photons can be absorbed at any depth $d$ within the WFC detector. The probability of absorption of a photon in a $\Delta d$ thick layer at a depth $d$ is proportional to

$$P(d) \propto e^{-d/l(E)}T(d)\Delta d,$$

where $l(E)$ is the mean free path of a photon with an energy $E$ and $T(d)$ represents the blocking by the three WFC detector wire grids and the cutoff due to the finite detector thickness.

The projection of $P(d)$ onto the sky plane influences the PSF. This takes the form of $D(E)\tan \alpha$, where $D(E)$ is the maximum depth for photons of energy $E$ and $\alpha$ is the off-axis angle.
Thus, the photon distribution projected on the detector plane at energies above $\sim 15$ keV shows an asymmetric tail which cuts off at positions corresponding to that of the grid planes and to the bottom of the detector (i.e., 3 mm on the detector plane for a source at an off-axis angle of $4^\circ$ at 30 keV; see in’t Zand 1992 for further details).

These effects have a significant impact on the source PSFs in the total map, creating a sort of “comet effect” in the PSF shape that becomes worse at higher energies, as Figure 4 shows. Thus for source searching we choose the 3–17 keV energy range in order to both maximize the instrument sensitivity and minimize the deformation of the PSF in the maps.

Following the failure of the gyroscopes on board the satellite, the star trackers were used to control the rotations and the pointing of the satellite (Tramutola et al. 2000). This procedure required those zones of the sky regularly observed (such as the Galactic center region and consequently the anti-Galactic center and the zone around the Crab Nebula) to be observed with the satellite (and WFC detector) in the same position with respect to the sky, and thus with the same bright stars in the star tracker field of view. As the INTEGRAL pointing strategy has demonstrated for coded mask instruments, observing the same sky zone with different pointing configurations can significantly reduce the background (Courvoisier et al. 2003) image artifacts. For this reason, the Galactic center zone (and the anti-center) has a significantly higher background in the WFC total mosaic map compared to the other sky zones where the serendipitous nature of the pointings has the same effect as the INTEGRAL pointing strategy. Moreover, the Galactic center zone has an intrinsically higher noise also in a single image, due to the presence of a large number of sources in the field of view which makes image deconvolution more difficult.

3. THE TABLE

3.1. Source List Generation

Two methods were used to create an initial source list. The first used a tool developed for the IBIS survey (Bird et al. 2007) that searched for excesses exceeding a local threshold set by a baseline statistical threshold scaled by the local rms fluctuations within the map. This tool is intended to suppress the detection of fake sources in areas of the map with high non-statistical fluctuations. A second method based on the SExtractor 2.4.4 software (Bertin & Arnouts 1996) has been used to cross-check the results with a bandpass filter (Gauss filter) to minimize the source confusion in crowded fields. The list of excesses was then checked manually. A baseline acceptance limit at the 4.8$\sigma$ level has been adopted, although we stress again that the effective threshold in areas of high systematic artifacts will be considerably higher, and thus the acceptance limit varies considerably from zone to zone of the map. For example, in the Galactic center region the local acceptance limit is at $\sim 12\sigma$. After acceptance, the source positions and fluxes were evaluated using a barycentering method to determine the centroid of the source profile. The mean flux of the sources was determined from the count rate at the position of the source maximum significance (the counts-to-flux conversion is obtained assuming a Crab-like spectrum for the sources). After all the checks, the final list contains 458 excesses above 4.8$\sigma$. Of these excesses, 404 were identified as sources while 54 were considered to be map artifacts because of the PSF shape or the proximity to an image structure. The sources in the final list were then classified by a process of correlation with other existing catalogs.
3.2. Position Error

The PSF distortion due to the "comet effect" and the presence of other systematic effects prevent us from simply extrapolating the point location accuracy from the mosaic maps with a fixed confidence level. In order to estimate the source location error radius of the WFC sources, we compared the positions of the known sources detected in the map with their best-known positions, applying a procedure similar to the one reported in Scaringi et al. (2010a). The best positions were extracted from the INTEGRAL general reference catalog (IGRC), considered to be one of the most recent and comprehensive compilations of accurate X-ray and hard X-ray positions (Ebisawa et al. 2003). We have taken into account only those sources in the IGRC with a position specified to better than 30′′, i.e., those providing a well-defined “reference” position; this was possible for a total of 204 sources detected by the WFC. Following the procedure described in Scaringi et al. (2010a), we plotted the offset between our positions and the reference ones, as a function of the WFCs S/N for these 204 sources, after which we binned the offset values in order to have enough statistical significance for each bin. This method can take into account both the systematic and the statistical errors as it makes no assumptions about the form of the position error. The best-fit curve for the 90% confidence radius, plotted in Figure 5, is

\[ Y = \frac{A(0)}{2} e^{A(1)} + A(2), \]

where \( A(0) = 3.21, A(1) = 1.41, \) and \( A(2) = 1.56. \) The errors reported in Table 3 are extrapolated from Figure 5.

It is important to note that the best positions for variable and transient sources are generally derived from the single observation with the highest sigma. The positions derived from the overall mosaic for these sources are essentially degraded by the many non-detections added when forming the final mosaic. Conversely, for faint persistent sources, the position extracted from the mosaics is the best that can be obtained and has the lowest error.

3.3. Comparison with the Previous WFC Catalog

A WFC catalog of sources was published by Verrecchia et al. in 2007 July. That work is based on the analysis of each single pointing and is optimized for transient source detection.
(a similar work, restricted to the Galactic plane zone, was published in Capitanio et al. 2004). Our work is instead based on the searching of mosaic maps and is primarily intended to identify persistent sources not necessarily visible in a single OP. For this reason, our list of sources is somewhat different from the one published in Verrecchia et al. (2007).

Verrecchia et al. (2007) list 253 sources while our catalog contains 404 sources; 222 sources are present in both catalogs. The 31 sources reported only in Verrecchia et al. (2007) are all faint sources detected in only one or two individual OPs, and thus as we expected they are not detected in the total map. In particular, within the 11 brightest sources listed only by Verrecchia et al. (2007), there are 5 sources for which there is a detection in the total map but the detection level is lower than 4.8σ. The other six sources are located near structures in our map or in noisy regions (like the Galactic center region) where the detection threshold is high.

As we expected, the 182 sources found only by us (shown in bold in Table 3) are mostly persistent or quasi-persistent. It is important to note that within these 182 sources, there are 17 IGR sources and 9 Swift sources that have been discovered only after the end of the BeppoSAX mission. Moreover, the list contains 10 new sources.

In order to verify and further quantify the intrinsic variability of the source populations in the two catalogs, we have inspected the statistical properties of light curves extracted for each source. We developed a tool for WFC light curve production that reads the flux (counts s^{-1} cm^{-2}) from the source position in each single WFC pointing image using The IDL Astronomy User's Library procedures. Unfortunately, any tool such as this will be affected by the problem reported by Verrecchia et al. (2007): the WFCs standard software does not totally correct the differences in flux due to the different position of the sources in the field of view of each WFC pointing. This effect adds a systematic error of about 10%.

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Table 3

BeppoSAX WFCs List of Sources

| Name            | R.A. (°) | Decl. (°) | σ   | Error (°) | Flux_{3–17 keV} | Flux_{17–28 keV} | Source Type | Subtype |
|-----------------|----------|-----------|-----|-----------|----------------|----------------|-------------|---------|
| IGR J00040+7020 | 0.913    | 70.307    | 7.7 | 3.3       | 0.2 \pm 0.1    | 0.5 \pm 0.1    | Sy2         | ...     |
| Mrk 335         | 1.591    | 20.199    | 7.4 | 3.3       | 0.4 \pm 0.1    | 0.6 \pm 0.1    | Sy1         | ...     |
| IRXS J000635.7–69030 | 1.660 | -68.979   | 6.6 | 3.5       | 0.2 \pm 0.1    | 0.4 \pm 0.1    | Unid        | ...     |
| QSO B0014+810   | 4.298    | 81.583    | 5.9 | 3.8       | 0.13 \pm 0.03  | 0.4 \pm 0.1    | QSO         | ...     |
| 4U 0022+63      | 6.333    | 64.148    | 189.6 | 1.6 | 5.9 \pm 0.6 | 1.4 \pm 0.2 | SNR         | ...     |
| V709 Cas        | 7.177    | 59.278    | 31.6 | 2.0       | 1.0 \pm 0.1    | 1.7 \pm 0.2    | CV          | IP      |
| IGR J00335+6126 | 8.346    | 61.428    | 5.6 | 3.9       | 0.2 \pm 0.1    | 0.2 \pm 0.1    | Unid        | ...     |
| 1RXS J003422.2–790525 | 8.540 | -79.077   | 9.3 | 3.0       | 0.2 \pm 0.1    | 0.5 \pm 0.1    | Sy1         | ...     |
| 1E S0033+59.5   | 8.920    | 59.804    | 39.3 | 1.9       | 1.3 \pm 0.2    | 1.5 \pm 0.2    | BL Lac      | ...     |
| IGR J00370+6122 | 9.256    | 61.338    | 11.8 | 2.7       | 0.4 \pm 0.1    | 0.3 \pm 0.1    | HMXB        | ...     |

Notes.

a A name in bold face indicates a new detection with respect to Verrecchia et al. (2007).

b Error circle radius extrapolated from Figure 5 with the systematic error included.

c Average flux estimation in mCrab (see Section 4.1 for details).

d Type classifications—AGNs: active galactic nuclei; BL Lac: BL Lac object; cluster: cluster of galaxies; CV: cataclysmic variable; HMXB: high-mass X-ray binary; LMXB: low-mass X-ray binary; QSO: quasar; RGal: Radio Galaxy; RSCVn: RS Canum Venaticorum variable; SNR: supernova remnant; Sy1: Seyfert 1 galaxy; Sy2: Seyfert 2 galaxy; unid: unidentified source; SiC: star cluster, XRB: galactic X-ray binary; XP: X-ray pulsar.

e Subtype classifications—A: atoll-type source (neutron star); B: burster (neutron star); Be: B-type emission-line star; BHC: black hole candidate; D: dipping; DN: dwarf nova; G: globular cluster X-ray source; IP: intermediate polar; M: microquasar, P: polar; symb: symbiotic star; SG: supergiant; Z: Z-type source.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Figure 6. Variability distribution of the catalog sources, shown in the form of the reduced $\chi^2$ when the light curve is compared to a model of a constant mean flux.

(A color version of this figure is available in the online journal.)

The intrinsic variability for each source in our data set was determined by performing a check for excess variance (i.e., a chi-squared test against a constant mean flux) for each of the light curves. As expected, the $\chi^2$ distribution is peaked around 1 (indicating a persistent source) with a long tail representing the variable sources (see Figure 6). Moreover, as Figure 7 shows, comparing the variability statistic of both the sources detected also in the previous catalog and the sources detected only in this catalog, it is clear that the former are intrinsically more variable.

3.4. Flux Errors

As discussed in the previous section, the image reconstruction algorithm does not make a full correction for the off-axis response of the WFC cameras, resulting in a systematic increase in the flux uncertainty of ~10% in any given OP.
The mosaicing process generally reduces the effects of this poorly corrected off-axis response by averaging the fluxes from many OPs taken with different pointings, meaning that the source flux is measured at many different off-axis angles. However, in some cases where, for example, the single observations are not pointed with a random configuration (as in the Galactic center region) or when the source is highly variable, the fluxes in the maps could be affected by a systematic error higher than the estimated 10%. However, a plot of the source fluxes versus exposures, as in Figure 8, does not indicate any source flux anomalies. Thus, the flux errors reported in Table 3 can be considered to include both the statistical and the systematic errors.

4. THE SOURCE SAMPLE

In terms of the sources themselves, the WFC-source-type distribution from this work is significantly different from the one reported by the previous WFC catalog and reflects the higher fraction of persistent sources in our catalog. This indicates that one must always be aware of the timescale of the sensitivity of surveys when using them—the hard X-ray sky varies on many timescales—and performing a source search on any one timescale inevitably introduces a bias toward different source types. In fact, as Figure 9 shows, our catalog has a higher number of typical persistent objects such as Seyfert 1 (Sy1), Seyfert 2 (Sy2), and clusters of galaxies. In particular, compared to the previous catalog, the number of Seyfert galaxies is increased by about three times for Sy1 and about seven times for Sy2, while the number of clusters of galaxies detected increases by about three times.

It is also noticeable that our catalog contains a higher number of unidentified sources with a distribution that traces the higher exposure zones of the map.

The low-mass X-ray binaries (LMXBs) are the most populated class of sources of this catalog. Reflecting the highly variable nature of these objects, their number is slightly lower than the one previously reported (the total mosaic map lost the faintest transient objects) and all of them have also been detected in Verrecchia et al. (2007) except for 1E 1743.1−2843, a faint (0.1–0.2 LE) and peculiar source classified as an LMXB with a persistent nature (Del Santo et al. 2006). 1E1743.1−2843 is a typical source for which our work is optimized.

The high-mass X-ray binaries (HMXBs) are mostly the same as those observed in the previous catalog. The new detections (seven sources) are all Be/XRB systems in which we caught either persistent or long-term outburst emission.

We detected 17 new cataclysmic variables (CVs); looking at the different types of CVs, mostly all the new objects found are intermediate polar (IP; 14 objects for a total of 17), the CV subtype with the harder spectra (see, e.g., Scaringi et al. 2010b), while there are three new detections of dwarf novae (DNs) out of a total of five sources (for a discussion on the hard X-ray spectra of DNs, see R. Landi et al. 2011, in preparation).

Figure 10 shows the averaged hardness ratio (HR) of all the sources, extracted from both the 3–17 keV and 17–28 keV mosaic maps. Even if the large errors allow only the extraction of basic information for faint sources, we can speculate about the global behavior of the luminous sources.
The bright source sample is mostly formed by XRBs; as Figure 10 shows, the HMXBs are the hardest emitters: nine of them show an HR value greater than 3. The two softest HMXBs are indeed LMC X-1 and LMC X-3, both of them are persistent sources often detected with a bright disk blackbody component (Yao et al. 2005). The hardest source of the entire sample is the HMXB GX 301−2, one of the most massive XRBs known (see, e.g., Leahy & Kostka 2009), while the hardest LMXB is 1E1740.7−2942 (a persistent source often in hard state; Bouchet et al. 2009) and GX 1+4 is an accreting X-ray pulsar (Ferrigno et al. 2007). However, for the most part, the LMXBs have HR values that lie between 0.5 and 1.5. In particular, the most luminous LMXBs show HR values below 1. This is in agreement with the expected behavior of an LMXB which is generally very bright during its soft state (McClintock & Remillard 2005). The huge differences between the XRB HRs are not only due to the intrinsic properties of these sources but are also due to the specific observations. With the XRBs being extremely variable, the averaged HR values depend strongly on the source spectral states at the time of the WFC observations and may not represent a real time-average hardness value.

We produced the log $N$−log $S$ for the most populous source types present in our catalog: the LMXBs and HMXBs. The distribution is only indicative because even if the sky coverage is virtually complete, the exposure is not uniform. Our log $N$−log $S$ distribution is consistent with the one reported in Grimm et al. (2002) both for HMXBs and for LMXBs. As Figure 11 shows, the latter present a cutoff and a flatter
behavior with respect to the former. The straight lines in Figure 11 represent the lower and the upper limits of the best-fit slopes reported by Grimm et al. (2002). Our plot, above about 2 mCrab, is in good agreement with Grimm et al. (2002) even if, in spite of a total sky coverage, no exposure correction has been added to our data: the exposure spans from 2 × 10^6 s to 20 × 10^6 s for LMXBs and 2.5 × 10^5 s to 15 × 10^6 s for HMXBs, respectively.

4.1. Searching for Transient Sources with Light Curves

As discussed in Section 3.3, we are able to extract (with some limitations) light curves for any point on the sky by extracting fluxes from the OP images. This method can be used to perform an additional search for and analysis of known sources, since it only needs the position of the selected source. As an example, Figure 12 shows both WFC and All-Sky Monitor (ASM)/RXTE light curves of the LMXB system XTE J1118+480.

This light curve tool is also useful to search for transient sources that are below the detection threshold in the total mosaic but are also too faint to be clearly detected in single OP images, falling somewhere between the capabilities of the two catalog search methods. A good example of this is the case of IGR J17091−3624 (in’t Zand et al. 2004). This transient XRB is not detected in the total mosaic but mosaicing only the WFC observations near the known outburst periods (1996 September and 2001 September) the source is clearly detected (Capitanio 2007). Obviously, this procedure implies that the position of the source and its outburst date(s) must be previously known, and this unfortunately significantly limits the application of this method.

4.2. The New Source Candidates

The new source candidates detected in the maps were chosen using three principal conservative criteria: a signal-to-noise ratio greater than 12 (set to cope with even the worst local sigma level in the mosaic map), an exposure higher than 4 × 10^6 s, the average exposure over the entire map (see Section 2), and a light curve that does not present any spikes in single images. In fact, we visually inspected several possible new transients and rejected all of them on the basis of their being at the image border or near a structure or presenting an unacceptable PSF. With our work being specifically optimized for faint persistent sources, we did not expect any new transient sources with respect to the previous catalog that was optimized for transient detection. Applying these criteria, 10 new source candidates have been selected (3% of the total number of sources).

We searched for these 10 new sources within the X-ray observation archives and through catalogs from other energy ranges. The fields containing the new WFC sources have never been observed in the X-ray energy range below 20 keV (except for the ROSAT all-sky survey that did not detect them) and they have not been detected above 20 keV in either Swift/Burst Alert Telescope or IBIS/ISGRI mosaics.
Confidence in these 10 new detections is strongly supported by the many other sources uncovered by the same technique that proved to be correlated with known sources. Of course, in this kind of work, it is always possible that some false detections will be included, and the new sources can only be truly verified by follow-up observations or detections in other instruments.

Table 4 summarizes the principal characteristics of these 10 sources; in particular, the last column reports the possible radio and infrared counterparts of some of the sources.

Another source, WFC J1818—1658, was initially added to the list of the new sources, but after a more accurate analysis it was identified as the supergiant fast X-ray transient SAX J1818—1703, as described below.

### 4.2.1. The Curious Case of WFC J1818—1658/SAX J1818.6—1703

SAX J1818.6—1703 is an anomaly within the WFC catalogs. This source, discovered by the WFC in 1998 (in’t Zand et al. 1998), was not automatically recognized in our mosaic map, and it is not reported in Verrecchia et al. (2007).

The best position found in the WFC map for our candidate WFC J1818—1658 lies 9′/8 away from SAX J1818.6—1703 with a calculated error radius of 2′, the source being detected at the 32.5σ level (in a sky zone with a local averaged background of about 10σ level). The source was automatically classified as a new source. A counterpart search in all Swift/X-Ray Telescope (XRT) and XMM-Newton/EPIC data with the source in the field of view did not discover any plausible counterpart within the 2′ radius error circle. Although the position of WFC J1818—1658 is consistent with a serendipitous XMM source, 2XMMi J181813.9—165724, detected by both Swift/XRT and XMM-Newton/EPIC, the flux expected for a 32.5σ level source in the WFC mosaic map should be 100 times greater than that of this faint XMM object.

On the other hand, we know from IBIS studies (Bird et al. 2009) that SAX J1818.6—1703 (with counterparts clearly detected in most of the XRT and XMM images analyzed) appears in the IBIS persistent search mosaics as a result of occasional outbursts and low-level emission that occur during its periastron passages every 30 days.

Looking at each single WFC observation after the first detection of the source (in’t Zand et al. 1998), there is a faint transient object that appears recurrently in the data. This object has a position that slightly oscillates between the positions of the two sources (SAX J1818.6—1703 and WFC J1818—1658). However, the period in which the source is visible is recurrent and consistent with the known flaring period of SAX J1818—1703 (30 ± 1 days; Bird et al. 2009; Zurita-Heras & Chaty 2009). Figure 13 shows some WFC single-OP detections during both the flaring and the quiescent periods.

We can say that the timing analysis indicates that WFC J1818—1658 and SAX J1818—1703 have a high probability of being the same source and the shifted position of SAX J1818.6—1703 is caused by the particular sky zone in which the source is situated. In fact, this turns out to be a pathological case in which all the defects of the WFC map reported in the previous sections (i.e., Section 2.1) are manifested together: SAX J1818.6—1703 lies in the field of view of the periodic observations of the Galactic center region, thus the same star tracker configurations had been used each time. Moreover, SAX J1818.6—1703 always lies at the border of these observations, and thus at a huge off-axis angle. We have used mean offsets throughout this work when discussing position errors, because we are aware that there can be a small subset of sources (like SAX J1818—1703) that have substantially larger errors. Quoting a 90% confidence level based on this subset would give a misleadingly high location error for the vast majority of our sources. Finally, except for the first detection (∼100 mCrab; in’t Zand et al. 1998), the source flares were very faint (∼1 mCrab), partly explaining why it has not been seen as a transient object, but is instead seen as a quasi-persistent emitter, just as it is in the IBIS survey analysis.

### 5. CONCLUDING REMARKS

The WFCs on the BeppoSAX satellite were designed primarily to detect bright transient sources flaring within their large field of view. Despite this, the quality and quantity of data recorded have provided a legacy archive of quasi-all-sky observations of the hard X-ray sky that has not been fully exploited.

We have successfully applied techniques developed for the INTEGRAL/IBIS survey to the BeppoSAX WFC data set, on the basis that the two instruments are intrinsically similar in imaging method and operation. Our main aim has been to improve the sensitivity to weaker, more persistent sources not detected within individual WFC observations. The production and searching of mosaic maps from the ensemble of individual pointing is a good method to achieve this goal for persistent or quasi-persistent sources.

The success of this approach is evident in the detection of 182 sources not previously recorded in WFC catalogs. Most of these are known sources, partly because of the surge in hard X-ray detections in the INTEGRAL/Swift era, but around 35 of these sources would have been new discoveries for BeppoSAX if found at the end of the mission. Even though this work is partly limited by the optimization of the WFC hardware...
Figure 13. Selected WFC single-OP flux images, expressed in counts s\(^{-1}\) cm\(^{-2}\), of the SAX J1818–1703/WFC J1818–1658 region during both periodic flaring activity and quiescent states. (A color version of this figure is available in the online journal.)

and software for transient source searching, this represents a success for the approach. From a technical viewpoint, the areas that could still be improved include the flux reconstruction for individual pointings (and hence light curve production) and the PSF distortion that limits the source location accuracy and useful energy range.

When used in combination with more recent all-sky hard X-ray surveys, this catalog provides a view of this highly variable sky in another epoch with similar sensitivity (better than 1 mCrab), and as such should be of value in any studies of variability in galactic and extragalactic hard X-ray sources.

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