Open Universe survey of Swift-XRT GRB fields: Flux-limited sample of HBL blazars

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ABSTRACT

Aims. The sample of serendipitous sources detected in all Swift-XRT images pointing at gamma ray bursts (GRBs) constitutes the largest existing medium-deep survey of the X-ray sky. To build such dataset we analysed all Swift X-ray images centred on GRBs and observed over a period of 15 years using automatic tools that do not require any expertise in X-ray astronomy. Besides presenting a new large X-ray survey and a complete sample of blazars, this work aims to be a step in the direction of achieving the ultimate goal of the Open Universe Initiative, which is to enable non-expert people to benefit fully from space science data, possibly extending the potential for scientific discovery, which is currently confined within a small number of highly specialised teams, to a much larger population.

Methods. We used the Swift deepsky Docker container encapsulated pipeline to build the largest existing flux-limited and unbiased sample of serendipitous X-ray sources. Swift deepsky runs on any laptop or desktop computer with a modern operating system. The tool automatically downloads the data and the calibration files from the archives, runs the official Swift analysis software, and produces a number of results including images, the list of detected sources, X-ray fluxes, spectral energy distribution data, and spectral slope estimations.

Results. We used our source list to build the LogN-LogS of extra-galactic sources, which perfectly matches that estimated by other satellites. Combining our survey with multi-frequency data, we selected a complete radio-flux-density-limited sample of high energy peaked blazars (HBL). The LogN-LogS built with this data set confirms that previous samples are incomplete below ~ 20 mJy.

Key words. galaxies: active – X-rays:galaxies – Methods: data analysis – Astronomical data bases:catalogues

1. Introduction

X-ray sky surveys have played a major role in astrophysics ever since the early days of X-ray astronomy (e.g. Giacconi et al. 1979). Outside the Galactic plane the main population of X-ray sources is that of active galactic nuclei (AGN, Brandt & Hasinger 2005), both jetted and non-jetted (Padovani et al. 2017), which reflects the fact that X-rays trace both the accretion onto super-massive black holes and the radiation output of relativistic jets. In this paper, which follows previous similar works by Pucetti et al. (2011) and Dai et al. (2015), we describe a serendipitous survey based on X-ray images taken when the Neil Gehrels Swift Observatory (Gehrels et al. 2004, hereafter...
Swift was pointing at gamma-ray bursts (GRBs) during its first 15 years of operation. Besides being based on the largest available data set, the main peculiarity of this survey is that it was generated and cleaned in an automatic way, without any visual or manual intervention. This was done using the Swift-DEEPSKY Docker pipeline, an innovative analysis tool developed in the context of the Open Universe initiative (Giommi et al. 2019, hereafter Paper I), which greatly simplifies X-ray image analysis and can be run on most personal or desktop computers, even by users with no experience in X-ray astronomy.

Since GRBs explode at random positions in the sky, this survey, after the removal of the target GRBs, constitutes an unbiased medium-deep view of the serendipitous X-ray sky that is suitable for population studies and for the estimation of the cosmological properties of cosmic sources of different types (Turriziani et al. 2019). The main improvement of this survey compared to Puccetti et al. (2011) and Dai et al. (2015) is a significant increase in the covered area, rather than reaching higher sensitivity. This is because the amount of exposure time dedicated by Swift to GRBs was largest at the beginning of the mission, and because the need to avoid human intervention in the flagging of spurious sources, especially in the deepest exposures close to the limits of the instrument, reduces the sensitivity to values that are somewhat above the theoretical limit.

In the following we concentrate on blazars, a remarkable type of AGN that emits non-thermal and highly variable radiation across the entire electromagnetic spectrum, from radio waves to very high-energy $\gamma$-rays (see e.g. Urry & Padovani 1995; Padovani et al. 2017), and probably also high-energy neutrinos (IceCube Collaboration et al. 2018; Padovani et al. 2018; Giommi et al. 2020). This unique property among extragalactic sources is due to the fact that, in addition to radiating through the process of accretion onto the central super-massive black hole, which is common to all AGNs, blazars also emit powerful radiation from a narrow relativistic jet that happens to be closely aligned to the direction of the Earth (Padovani et al. 2017).

Blazars come in different types: flat spectrum radio quasars (or FSRQs), whose optical spectrum shows broad emission lines just like normal quasi stellar objects (QSOs) and BL Lacertae objects (or BL Lacs) that show only very narrow lines or a completely featureless optical spectrum. Blazars are further classified according to the shape of their spectral energy distribution (SED) into low, intermediate, and high-energy peaked objects, LBL (or LSP), IBL (or ISP), and HBL (or HSP) respectively, depending on the energy at which the power of their synchrotron emission peaks in their SED (Padovani & Giommi 1995; Abdol et al. 2010). In this paper we adopt the original HBL/IBL/LBL nomenclature.

One of the still poorly understood properties of blazars concerns their cosmological evolution, which for BL Lacs has been found to be different from that of all other types of AGNs and star-forming galaxies (see e.g. Maccacaro et al. 1984; Giommi et al. 1999; Rector et al. 2000; Turriziani et al. 2019). Early studies (Rector et al. 2000; Wolter & Celotti 2001) based on small X-ray selected samples have shown that BL Lacs, and in particular those of the HBL class, display no or even negative cosmological evolution. This peculiar behaviour has been confirmed in radio-flux-limited samples of the most extreme HBLs (Giommi et al. 1999). More recently Ajello et al. (2014) showed that even in the case of a $\gamma$-ray selected sample, low-luminosity HBL BL Lacs show strong negative evolution. Despite their extreme rareness, HBL blazars play a crucial role in current and future high- and very-high-energy $\gamma$-ray surveys, (The Fermi-LAT collaboration 2019; CTA Consortium 2019) and, probably, in multi-messenger astrophysics (Giommi et al. 2020, and references therein). For the first time, we present an X-ray survey that is large and deep enough to allow the selection of a statistically complete flux-limited sample of blazars of this type with radio flux-densities $\lesssim 20$ mJy. This work also demonstrates that complex data analysis projects can in principle be carried out by non-experts, one of the main goals of the United Nations Open Universe initiative.

2. Open Universe Initiative

Open Universe (Giommi et al. 2018) is an initiative under the auspices of the United Nations Office for Outer Space Affairs (UNOOSA) with the objective of making astronomy and space science data more openly available, easily discoverable, free of bureaucratic, administrative or technical barriers, and therefore usable by the widest possible community, from professional researchers to all people interested in space science and astronomy, including students, non-professionals, and amateur scholars of the subject. One of the main goals of Open Universe is to contribute to increase the productivity of space research, and stimulate a significant acceleration towards the democratisation of space science, therefore contributing to the achievement of the United Nations Sustainable Development Goals (SDGs)\(^1\). Another goal is to contribute to the development of open data and web interface requirements, so as to make space science data more understandable and attractive (reducing for example the problem of information overload, also known as inforbosity), implementing lessons learned and recommendations arising from behavioural economics findings (Thaler & Sunstein 2008; Sunstein 2013), to broaden the consultation of scientific data and to bring new students and non-specialists closer to science.

The initiative was proposed by Italy to the Committee On the Peaceful Uses of Outer Space (COPUOS) in 2016, and is now actively carried out by a number of Member States and international institutions under the coordination of UNOOSA. In line with the objectives of Open Universe, we recently started a series of activities aimed at the generation of transparent space science data products.

3. Gamma-ray bursts and Swift

The Swift satellite was conceived and specifically designed as a panchromatic space observatory dedicated to the observations of GRBs, from the detection of the explosion in the large field of view of its Burst Alert Telescope (BAT Barthelmy et al. 2005) operating in the hard X-ray band, to the fast and automatic follow up by means of the onboard narrow fields instruments XRT (Burrows et al. 2005) and UVOT (Roming et al. 2005) operating in the soft and medium X-ray and in the optical and UV bands, respectively. Gamma-ray bursts are the most powerful transient sources in the Universe. They are located at cosmological distances and are detected at a rate of approximately one

\(^1\) http://www.unoosa.org/oosa/oosadoc/data/documents/2018/aac.105/aac.105175.0.html
event per day at random positions on the celestial sphere. Assuming that GRBs radiate isotropically, their energy release in X-rays and gamma rays lies in the range $10^{51} - 10^{54}$ erg. Gamma-ray bursts consist of an intense and highly-variable emission in gamma rays called prompt emission, followed by the so-called afterglow phase, a long-lasting activity in which the observed flux decreases with time and the emission energy shifts to lower values (X-rays, optical, IR, and radio bands). The prompt phase usually lasts from milliseconds to minutes, while the afterglow duration can be from hours to weeks. No two GRBs with identical light curves have so far been detected. The prompt emission is non-repeating, non-periodic, highly variable, and very energetic.

The study of GRBs and the modelling of their progenitors and emission mechanisms is possible thanks to the many space and ground-based observatories operating in different energy bands that have provided or currently provide large amounts of data, part of which can also be used for other purposes, as in this paper. During the first 15 years of operation, from shortly after launch in late November 2004 until the end of 2019, Swift observed over 1,300 GRBs with the XRT telescope. A Hammer-Aitoff plot of their positions in Galactic coordinates is shown in Fig.1.

Fig. 1. Hammer-Aitoff plot in Galactic coordinates of all the Swift-XRT fields centred on GRBs and observed in PC readout mode. The 1,046 fields at Galactic latitude larger than ten degrees used for the extragalactic survey are shown in red.

4. XRT data analysis

Following the approach adopted in Paper I, we used the Docker container\(^2\) version of the Swift\(_{deepsky}\) pipeline to analyse all the Swift-XRT observations pointing at GRBs and carried out in photon counting (PC) readout mode (Burrows et al. 2005; Giommi et al. 2019). The Swift\(_{deepsky}\) software, built on top of the official HEASoft data reduction package \(^3\), automatically performs the following tasks:

- downloading low-level data and calibration files from one of the official Swift archives;
- generation of exposure maps and X-ray images;
- stacking of exposure maps and X-ray images;
- point-like source detection based on the slide-cell and background determination methods built in the XIMAGE package. In this process the detection threshold is set to a probability of $10^{-4}$ that the photon excess is due to a fluctuation of the background and to a minimum signal-to-noise ratio of two. These conditions ensure that the expected number of false-positives due to statistics is less than one every ten fields;
- estimation of the count rates in three energy bands (0.3-1 keV, 1-2 keV, and 2-10 keV) based on the XIMAGE/SOSTA tool;
- estimation of spectral parameters based on the count rates in the three energy bands considered and on the

\(^2\) https://www.docker.com
\(^3\) https://heasarc.gsfc.nasa.gov/docs/software/lheasoft

Fig. 2. Exposure time of the stacked images centred on GRBs as a function of time. A clear trend towards lower exposures with time is apparent, reflecting the fact that GRBs were followed for longer times at the beginning of the Swift mission.

Fig. 3. Plot of the 0.3-10 keV XRT count rate versus effective exposure time. The minimum detectable count rate, which determines the survey limiting sensitivity, is delimited by the black dashed line.
The deepsky pipeline was run on all the 1,332 stacked XRT fields centred on as many GRBs, 1,332 of which passed the quality check mentioned above. GRBs with long and frequent exposures, in order not to loose any details of the evolution of the X-ray emission, were summed into a single X-ray image, resulting in 1,332 X-ray fields of the OUSXG Survey. Figure 4 plots the sky coverage for the cases of the full survey and for the subsample of high Galactic latitude ($|b| > 10^\circ$) XRT fields.

At higher exposures the background level is no longer negligible, and the curve gradually flattens until it reaches the slope of 0.5 at $\sim 5 \times 10^4$ s where the survey starts to be fully background limited.

To properly take into account the XRT sensitivity dependence in different parts of the field of view and the non-perfectly overlapping images, we add the exposure maps of the single pointings and we divide the resulting stacked map into 1,600 sub-images, 24x24 arc-seconds in size, roughly matching the size of the XRT point spread function. The limiting sensitivity of each sub-image is then estimated from the low level detectable count rate (as described above), converted to 0.5-2.0 keV X-ray flux assuming a power law spectrum with an energy index of 0.9, absorbed by the amount of Galactic hydrogen column (NH) in the pointing direction. The overall sky coverage, that is, the total area of sky covered at any given sensitivity, is obtained by summing the contributions of all sub-images of all the GRB fields of the OUSXG Survey.

5. Sample of serendipitous X-ray sources

The Swift deepsky pipeline was run on all the 1,332 stacked XRT fields using two Open Universe medium-sized Linux machines located in Rome (ASI) and Pescara (ICRANet). The processing was completely unsupervised and lasted less than two days. The set of serendipitous point-like X-ray sources that were detected in this process and passed the automatic data cleaning procedure described in Paper I includes 31,227 objects, 27,740 of which are located at high Galactic latitudes ($|b| > 10^\circ$). The effective exposure time at the position of each source is calculated taking into account the image exposure time, vignetting correction, and charge coupled device (CCD) dead pixels and dead rows. This is obtained by stacking the exposure maps of every pointing that contributes to the stacked X-ray image. This sample is a flux-limited unbiased survey of the X-ray sky once the GRBs target of the observations are removed.

5.1. Comparison with other Swift XRT catalogues

A number of catalogues of serendipitous X-ray sources have appeared in the literature. Among these we distinguish between general purpose, thematic, and survey catalogues. The first ones (e.g., D'Elia et al. 2013; Evans et al. 2014, 2019) generally include all X-ray sources detected by Swift-XRT (or other imaging X-ray telescopes) up to a certain date, typically several months before the publication of the list. These are traditional catalogues that reflect the sequence of observations performed by the satellite but do not provide accurate information about the area of sky covered as a function of sensitivity nor the many details that are essential to control the observational biases resulting from the complex scientific and guest observer programs that determine the composition of the archive. Thematic catalogues concentrate on a specific type of sources, like for example blazars, as in Giommi et al. (2019), or GRBs, while survey catalogues (e.g., Puccetti et al. 2013; Dai et al. 2015, and this work) are designed for the purpose of statistical use and therefore pay attention to the need to control observational biases and provide details about the sky coverage as a function of sensitivity. So far, all these catalogues

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4 [https://openuniverse.asi.it](https://openuniverse.asi.it)
5 empirically calculated from the data shown in the figure.
have been generated by teams of experts and have been published with an irregular cadence of one every few years. The approach presented in Paper I, and replicated here in a survey context, constitutes an innovative type of catalogue that is more dynamical and potentially always up to date, since the Swift deepsky software provides the possibility of updating an existing catalogue by running the software on new observations by anyone and on most computers at any time.

5.2. Cross-matching with catalogues of known astronomical sources

To identify at least a fraction of our serendipitous X-ray sources, we have cross-matched the OUSXG sample with several astronomical source lists using a matching radius of 10 arc-seconds for the case of catalogues of point-like objects and 90 arc-seconds for clusters of galaxies. The largest table used is the "million quasars" catalogue (Milliquas, version 6.4 Flesch 2015), which includes nearly two million AGNs. This resulted in over 6,000 matches (or about 20% of the total), including sources with redshift up to 5.6. Since we are interested in finding blazars, we also cross-correlated our sample with the Open Universe list of blazars, which combines the 5BZCAT (Massaro et al. 2015), the 3HSP (Chang et al. 2019), and the 4LAC from The Fermi-LAT collaboration (2019) catalogues, and is the largest table of known blazars, obtaining only 34 matching sources. In order to identify blazars that are still uncatalogued, we cross-matched the sample with tables of radio sources such as the NVSS (Condon et al. 1998) or the SUMSS21 (Manch et al. 2003) catalogues, resulting in nearly 900 matches. Table 1 summarises the results of the cross-matching with some of the main catalogues of known astronomical sources, while Table 2 gives the number of OUSXG sources that are common to other recent X-ray catalogues. The choice of a 10 arc-seconds matching radius is somewhat larger than the typical positional error of XRT serendipitous sources. We have chosen this value to take into account the positional uncertainties of the other catalogues, which can be up to a few arc-seconds. Given the density of some of the catalogues this could lead to a number of false positive matches. By using the technique of shifting the coordinates of one of the matching tables, we estimate that this problem is limited to $\sim 1\%$ or less.

5.3. Comparison with other X-ray surveys

In this section we compare the OUSXG sample to a number of existing or upcoming X-ray surveys. Figure 5, adapted from Merloni et al. (2012), plots the sensitivity of the most important existing or upcoming X-ray surveys as a function of the area of sky covered. The deepest fields, obtained investing several mega-seconds of exposure time of the largest operating X-ray observatories like Chandra and XMM, reach sensitivities well below $\sim 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ but cover very small areas of sky, whereas the Rosat All Sky Survey (RASS, Voges et al. 1999), still the only available all sky survey, is relatively shallow, only reaching a flux limit of a few times $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5-2.0 keV band. Below $\sim 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ OUSXG (represented by the dashed green line) is currently the largest survey available. Even when the e-Rosita all sky survey (Merloni et al. 2012) is completed, at fluxes of a few times $10^{-15}$ erg cm$^{-2}$ s$^{-1}$, OUSXG will still be complementary to it, since in this sensitivity regime e-Rosita will only cover a relatively small fraction of sky near the ecliptic poles, whereas the fields of OUSXG are located in all parts of the sky.

\[ http://quasars.org/milliquas.htm \]
5.4. X-ray LogN-LogS of extragalactic point-like sources

We have used the OUSXG sample, limited to |b| > 10°, and the corresponding sky coverage shown in Fig. 4 to build the (integral) X-ray LogN-LogS of extragalactic sources down to a flux limit of 1.5 × 10^{-15} erg cm^{-2} s^{-1}. Below this flux the survey only covers a few square degrees of sky and the automatic method used for the source detection starts becoming somewhat unreliable. The results are plotted in Fig. 6 superposed to the estimations of other X-ray satellites. The data is tabulated in Table 4. Given the remarkably good agreement with previous findings we can deduce that:

- the subset of serendipitous point-like X-ray sources with flux > 1.5 × 10^{-15} erg cm^{-2} s^{-1} in the 0.5-2.0 keV band (26,217 objects) detected at Galactic latitudes larger than 10 degrees can be considered to be a statistically well-defined sample affected by a negligible fraction of spurious sources;
- the sky coverage shown in Fig. 4 is accurate and can be used, together with suitable sub-samples, to investigate the statistical properties of specific populations of X-ray sources.

5.5. Serendipitous blazars

In this paper we exploit the X-ray sensitivity of the OUSXG survey, which is nearly two orders of magnitude better compared to the RASS to correct the incompleteness of the largest existing table of HBL blazars, the 3HSP sample (Chang et al. 2019). In the following we limit ourselves to building a deep radio-flux-density-limited sample of HBL blazars and use it to estimate its radio LogN-LogS. A detailed study of the statistical properties (in particular the amount of cosmological evolution) of HBL blazars is the subject of a parallel paper (Chang et al. 2020, in preparation) where the sample selected here will be combined with the larger (but incomplete at faint radio flux densities) sample compiled by Chang et al. (2019) using multi-frequency data and the RASS survey (Voges et al. 1999).

Table 1. Results of the cross-matching of the clean sample with catalogues of known objects.

| Catalogue name | Type | No. of matches | Matching radius (") |
|----------------|------|----------------|---------------------|
| 4SXPS^7         | QSOs | 6,058          | 10                  |
| 5BZCAT^8, 3HSP^9 |      |                |                     |
| 4LAC^10         | Blazars | 34          | 10                  |
| ASCC^11         | Stars | 676           | 10                  |
| Principal Galaxies |      |                |                     |
| Catalog PGC^12 | Galaxies | 25          | 10                  |
| NVSS^13, SUMSS21^14 | Radio sources | 889    | 10                  |
| Zwicky, Abell^15 | Clusters |            |                     |
| Plancksz, SWXCS^16 | of galaxies | ~140 | 90                  |

The availability of complete flux-limited samples is essential for the investigation of the cosmological properties of HBL blazars, especially below ~20-30 mJy, where they appear to show strong signs of cosmological de-evolution (Maccacaro et al. 2015; Flesch (2015); Massaro et al. (2015); Chang et al. (2019); Kharfenko & Roesser (2009); Paturel et al. (2003); Condon et al. (1998); Manch et al. (2003); Zwicky et al. (1968); Abell et al. (1989); Planck Collaboration (2016); Liu et al. (2015); Evans et al. (2019); Webb & al. (2020); Evans et al. (2020); Dai et al. (2015).
which corresponds to a source that matches a radio source in the NVSS or SUMSS21 catalogues and with an X-ray to radio flux ratio in the range observed in the sample of known HBL sources (Chang et al. 2019). All SED data were retrieved using both the VOU-Blazar tool (Chang et al. 2020) and the ASI space science data center (SSDC) SED builder21. In order to get objective \( \nu_{\text{peak}} \) values for our sources we used a newly developed deep-learning estimator called \( \text{DNNSed}\)22. The tool uses the multi-frequency (radio to \( \gamma \)-ray) data available for each blazar, to estimate \( \nu_{\text{peak}} \) taking into account that some of the emission may not come from the jet, but rather from the host galaxy or from the so-called "blue bump". The algorithm has been trained using all the blazars included in the 5BZCat and 3HSP catalogues (Massaro et al. 2015; Chang et al. 2019) for which a robust \( \nu_{\text{peak}} \) value is available.

The input to the \( \text{DNNSed} \) tool is a SED file retrieved by means of the VOU-Blazars SED builder (Chang et al. 2020). This multi-wavelength data set is then segmented into 33 energy bins from radio to \( \gamma \)-rays, depending on the availability of experimental data. For a given SED the median and its variance are calculated for each of the bins and fed into the neural network. From the comparison between the \( \nu_{\text{peak}} \) values estimated by the tool and those of a set of blazars in a control sample, we verified that our \( \nu_{\text{peak}} \) values are unbiased and reliable up to \( \nu_{\text{peak}} \) values of \( \sim 5 \times 10^{17} \) Hz, with a typical uncertainty of 0.5 dex. Finally, a visual inspection was carried out to validate the HBL nature of each candidate. We realise that the uncertain

**Table 3.** HBL blazars in the complete radio-flux-density-limited sample.

| Source name | Blazar name | Detected in RASS survey | Radio flux d. (mJy) | Redshift | X-ray flux 0.5-2.0 keV (erg cm\(^{-2}\) s\(^{-1}\)) | Log(\( \nu_{\text{peak}} \)) |
|-------------|-------------|------------------------|-------------------|---------|------------------------------------------|---------------------|
| OUSXGJ005224+5003.5 | – | no | 9.1 | 0.53 | 2.97E-14 | 15.9 |
| OUSXGJ005434–3846.2 | – | no | 22.3 | 0.507 | 4.11E-14 | 15.4 |
| OUSXGJ010346+3401.3 | – | no | 3.6 | 0.49 | 1.65E-14 | 15.9 |
| OUSXGJ015946+0900.0 | 3HSPJ015945.1+090002 | no | 9.9 | 0.63 | 3.78E-14 | 15.9 |
| OUSXGJ0201217–0221.9 | 3HSPJ021216.9–022155 | yes | 25.3 | 0.250 | 2.04E-14 | 17.1 |
| OUSXGJ0205240–1900.5 | 3HSPJ022539.7–190035 | no | 5. | 0.40 | 1.10E-13 | 16.2 |
| OUSXGJ0303405–3956.3 | – | no | 4.2 | 0.31 | 2.95E-14 | 15.8 |
| OUSXGJ0305254+2709.9 | – | no | 3.8 | 0.62 | 1.88E-14 | 15.9 |
| OUSXGJ074240–6211.0 | 3HSPJ074419.1–621100 | yes | 48.7 | 0.38 | 2.75E-13 | 16.4 |
| OUSXGJ075119–0027.8 | – | no | 26.5 | 0.27 | 1.58E-13 | 16.1 |
| OUSXGJ0800557+0732.5 | 3HSPJ080056.5+073235 | no | 8.1 | 0.44 | 1.19E-12 | 15.6 |
| OUSXGJ0832511–3300.1 | 3HSPJ083251.5–330011 | yes | 4.5 | 0.672 | 1.17E-12 | 18.0 |
| OUSXGJ0855434+1103.2 | 3HSPJ085542.8+110315 | yes | 14.8 | 0.300 | 6.66E-14 | 15.8 |
| OUSXGJ0856074+7118.8 | 3HSPJ085607.3+711851 | no | 19.0 | 0.31 | 1.09E-13 | 16.1 |
| OUSXGJ0916524+5238.4 | 3HSPJ091651.9+523828 | yes | 139.1 | 0.190 | 9.45E-13 | 16.3 |
| OUSXGJ0934303–172121 | 3HSPJ093430.1–172121 | yes | 29. | 0.250 | 2.24E-12 | 16.2 |
| OUSXGJ111803–1531.0 | – | no | 6.5 | 0.47 | 1.80E-14 | 15.7 |
| OUSXGJ113428–0702.1 | – | no | 4.7 | 0.31 | 3.29E-14 | 15.6 |
| OUSXGJ1223265–1055.9 | 3HSPJ122326.5–105600 | no | 11. | 0.19 | 1.44E-13 | 16.1 |
| OUSXGJ1242311+7634.2 | 3HSPJ124232.3+763418 | yes | 8.8 | 0.48 | 3.15E-13 | 16.4 |
| OUSXGJ1255101+2804.2 | 3HSPJ125509.8+280418 | yes | 1.7 | 0.69 | 1.20E-13 | 16.9 |
| OUSXGJ154535–0019.4 | 3HSPJ154534.7–001928 | yes | 6.6 | 0.60 | 1.30E-14 | 15.7 |
| OUSXGJ215413+0004.3 | 3HSPJ215412.8+000423 | no | 4.3 | 0.217 | 3.00E-14 | 15.9 |

\(^{a}\)Uncertain. \(^{b}\)More than one possible optical counterpart.
tainty in the determination of $\nu_{\text{peak}}$ and the presence of spectral variability in poorly sampled SEDs might induce a small level of misclassification. Based on our long experience with blazars SEDs we feel that this potential problem should affect no more than one or two sources in the sample. A more precise estimation of this effect would require detailed simulations, which is clearly beyond the scope of this paper.

The set of HBL blazars selected by us constitutes a radio-flux-limited sample that is statistically complete down to the flux density limits of the NVSS and SUMSS surveys. It only includes 23 objects, which is indeed a tiny fraction (<0.1%) of the total number of serendipitous sources in the OUSXG survey, most of which are expected to be radio quiet QSOs (Brandt & Hasinger 2005), reflecting the extremely low space density of HBL blazars compared to that of all other types of AGN. Table 3 presents the sample of HBLs selected in this work. Columns 1 and 2 give the OUSXG name of the source and the 3HSP name, if the source is included in the 3HSP catalogue; Column 3 specifies if the source was detected in the RASS survey; column 4 gives the radio flux density at 1.4 GHz (or 0.8 GHz) from the NVSS (SUMSS) catalogue; column 5 gives the redshift if available; column 6 gives the 0.5-2.0 keV flux, and the last column gives the $\nu_{\text{peak}}$ as estimated by the DNNSED tool.

A detailed analysis of the cosmological properties of HBL sources will be presented in a dedicated paper (Chang et al. 2020, in preparation). Here we only derive their radio LogN-LogS and compare it to the one presented in Chang et al. (2019), which was based on a sample with some degree of incompleteness at low radio flux density values. The radio logN-LogS of our sample of HBLs is shown as red filled circles in Fig. 8, together with that estimated using the sub-sample of 3HSP blazars included in the RASS (blue filled circles) and the data tabulated in Table 5. As expected, a clear underestimation of the source density in the 3HSP sample is clearly present at radio flux densities below approximately 20 mJy.

### Table 4. Data for the X-ray LogN-LogS shown in Fig. 6.

| 0.5-2.0 keV flux (erg cm$^{-2}$ s$^{-1}$) | Number density (deg$^{-2}$) |
|----------------------------------------|----------------------------|
| 1.50 × 10$^{-15}$                     | 661. ± 8.5                 |
| 2.38 × 10$^{-15}$                     | 403. ± 3.6                 |
| 4.77 × 10$^{-15}$                     | 268. ± 2.3                 |
| 5.97 × 10$^{-15}$                     | 171. ± 1.3                 |
| 9.46 × 10$^{-15}$                     | 98. ± 0.9                  |
| 1.50 × 10$^{-14}$                     | 53. ± 0.6                  |
| 2.38 × 10$^{-14}$                     | 26.5 ± 0.42                |
| 3.77 × 10$^{-14}$                     | 12.7 ± 0.28                |
| 5.97 × 10$^{-14}$                     | 6.1 ± 0.19                 |
| 9.46 × 10$^{-14}$                     | 3.1 ± 0.14                 |
| 1.50 × 10$^{-13}$                     | 1.55 ± 0.10                |
| 2.38 × 10$^{-13}$                     | 0.82 ± 0.07                |
| 3.77 × 10$^{-13}$                     | 0.40 ± 0.054               |
| 5.97 × 10$^{-13}$                     | 0.19 ± 0.042               |

### Table 5. Data for the radio LogN-LogS of HBL blazars shown in Fig. 8.

| Flux density (mJy) | Number density (deg$^{-2}$) | Number density (deg$^{-2}$) |
|-------------------|-----------------------------|-----------------------------|
| 3.50              | 5.27 ± 0.14 × 10$^{-2}$     | 1.43 ± 0.32 × 10$^{-1}$     |
| 6.56              | 4.24 ± 0.12 × 10$^{-2}$     | 6.22 ± 1.21 × 10$^{-2}$     |
| 12.30             | 2.97 ± 0.10 × 10$^{-2}$     | 3.38 ± 0.41 × 10$^{-2}$     |
| 23.05             | 1.84 ± 0.08 × 10$^{-2}$     | 1.85 ± 0.10 × 10$^{-2}$     |
| 43.21             | 9.48 ± 0.56 × 10$^{-3}$     | 9.48 ± 0.66 × 10$^{-3}$     |
| 81.00             | 4.37 ± 0.37 × 10$^{-3}$     | 4.37 ± 0.43 × 10$^{-3}$     |
| 151.83            | 1.77 ± 0.23 × 10$^{-3}$     | 1.77 ± 0.29 × 10$^{-3}$     |
| 284.60            | 8.63 ± 1.60 × 10$^{-4}$     | 8.63 ± 2.15 × 10$^{-4}$     |
| 533.48            | 2.68 ± 0.90 × 10$^{-4}$     | 2.68 ± 1.38 × 10$^{-4}$     |
| 1000.00           | 8.78 ± 5.07 × 10$^{-5}$     | 8.78 ± 8.54 × 10$^{-5}$     |

### 7. Availability of Data products

As in the case of Paper I, all the data products generated by this work comply with the principles of transparency put forward by the Open Universe initiative, and are available as high-transparency digital data products in different formats and in a variety of online services. In particular:

- All X-ray images in HIPS format are available from the Open Universe portal under the "Swift XRT" button, via the CDS Aladin visualiser (Bonnarel et al. 2000; Boch & Fernique 2014);
- The sky coverage of the survey and the catalogue that give the same parameters as in Paper I, including positions, integrated count rates and fluxes in different energy bands, spectral slopes, and four SED points, can be
HBL blazars are the rarest type of AGNs and therefore the selection of sizable samples requires large-area, relatively deep X-ray surveys. Although OUSXG is much larger than previous similar surveys, it only covers approximately 0.5% of the sky, and our complete sample of HBL blazars is relatively small, including only 23 objects. Despite their rarity, JHLL selected objects are the brightest in the high-energy photon sky. Building large samples of these objects is therefore an important contribution to the future of high-energy photon astronomy and multi-messenger astrophysics. Considering all Swift observations, that is, not only those centred on GRBs, the area of sky covered by the XRT telescope reaches about 10% of the sky. The Swift-XRT archive therefore holds the potential for the discovery of about a few hundred new faint HBL blazars. Although the complex selection biases would make this sample hardly usable for detailed statistical studies, it would be very valuable for the reasons mentioned above.

8. Conclusion

As part of the activities of the Open Universe initiative we used the Swift-deepsky Docker pipeline to process all the X-ray images pointing at GRBs generated by Swift-XRT over the last 15 years, from launch to the end of 2019. Our results can be summarised as follows:

- The use of the Swift-deepsky pipeline, which does not require any expertise in X-ray astronomy, associated with effective cleaning algorithms, allowed us to build a sample of serendipitous X-ray sources that is sufficiently clean to be used for statistical purposes without any visual or manual intervention.
- Using an X-ray flux limited sub-sample of approximately 26,000 high Galactic latitude sources, we have calculated the X-ray LogN-LogS of extragalactic sources, and showed that it is in excellent agreement with previous measurements.
- We have built a deep radio-flux limited sample of 23 HBL blazars that, combined with larger (and brighter) samples selected using the RASS survey, is suitable for detailed statistical analyses to be presented in a future paper (Chang et al. 2020, in preparation).
- The radio LogN-LogS of our sample of HBL blazars shown in Fig. 8 clearly implies that the 3HSP sample (and likely all previous samples) of radio faint ($f_r \lesssim 20$ mJy) HBL blazars suffer from significant incompleteness. The cosmological properties of this type of object estimated with early samples selected in not very deep X-ray surveys might need to be revised based on complete samples that benefit from deep X-ray detections.
- All data, including the sky coverage of the survey, are available through Open Universe and in other services.

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