An XMM–Newton catalogue of BL Lacs*

I. de la Calle Pérez1, N. Álvarez Crespo2, E. Racero3 & A. Rouco4

1 Quasar Science Resource S.L. for the European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain e-mail: icalle@sciops.esa.int
2 European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain
3 Serco Gestión de Negocios SLU for the European Space Agency (ESA), European Space Astronomy Centre (ESAC), Camino Bajo del Castillo s/n, 28692 Villanueva de la Cañada, Madrid, Spain
4 Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA) and Department of Physics and Astronomy, Northwestern University, 1800 Sherman, Evanston, IL, 60201, USA

January 13, 2022

ABSTRACT

Aims. We present an XMM–Newton catalogue of BL Lac X-ray, optical, and UV properties based on cross-correlation with the 1151 BL Lacs listed in the fifth edition of the Roma–BZCAT.

Methods. We searched for the X-ray counterparts to these objects in the field of view of all pointed observations in the XMM–Newton archive over nearly 20 years of mission. The cross-correlation yields a total of 310 XMM–Newton fields which correspond to 103 different BL Lacs. We homogeneously analysed data from the three EPIC cameras (X-ray) and OM (optical/UV) using the XMM–Newton SAS software, and produced images, light curves, and spectral products for BL Lacs detected in any of the three EPIC cameras. We tested two different phenomenological models, log parabola and power law, with different variations of the absorbing column density and extracted their parameters. We derived time-variability information from the light curves following well-established statistical methods and quantified variability through statistical indicators. OM magnitudes and fluxes were computed wherever possible.

Results. We see that the log parabola model is preferred over the power law model for sources showing higher fluxes, which might indicate that curvature is intrinsic to BL Lacs and is only seen when the flux is high. We present the results of our analysis as a catalogue of X-ray spectral properties of the sample in the 0.2 - 10 keV energy band as well as in the optical/UV band. We complete the catalogue with multi-wavelength information at radio and γ-ray energies.

Key words. BL Lacertae objects: general - galaxies: active - X-rays: galaxies - catalogues

1. Introduction

According to the unified scheme of active galactic nuclei (AGNs), a blazar is considered to be a radio-loud AGN that displays highly variable, beamed, non-thermal emission covering a broad wavelength range from radio to γ-ray energies (Urry & Padovani 1995). The properties of the blazar non-thermal emission suggest a relativistic origin in a jet oriented at a small angle to our line of sight (Blandford & Rees 1978). The blazar class encompasses BL Lacertae (BL Lac) objects and flat-spectrum radio quasars (FSRQs). The most striking difference between the two lies in their optical spectra, with the former showing weak or no emission or absorption lines (EW < 5 Å, Stickel et al. 1991) and the latter strong broad emission lines. One difficulty in the study of BL Lacs is indeed that in many cases it is not possible to measure any redshift because of a lack of features in their optical spectra (see e.g. Álvarez Crespo et al. 2016). Blazars, and in particular BL Lacs, are very strong γ-ray emitters, being the most numerous extragalactic sources at high energies (see Acero et al.[2015] Nolan et al.[2012] Abd et al.[2010b]).

Observationally, the spectral energy distribution (SED) of blazars in a νFν representation shows two broad distinctive peaks (see e.g. Padovani & Giommi[1995]). The most widely accepted interpretation of the first bump of the SED is that it is due to synchrotron radiation of relativistic electrons moving along the jet. Different models offer alternative solutions as to the origin of the second spectral component, namely leptonic or hadronic. In the leptonic model, the second peak is the result of inverse Compton (IC) scattering of low-energy photons to high energies by the very same electrons that produce the synchrotron peak. The up-scattered photons can be the synchrotron photons themselves (self-synchrotron Compton model, SSC; Ghisellini 1999, Ghisellini et al.[1992]) or ambient photons of different origins (external Compton model, EC; see review Sikora & Madejski 2001). On the other hand, hadronic models establish the origin of the second peak as synchrotron emission from high-energy protons or photoproduction induced by accelerated protons (see e.g., Mannheim[1996] Aharonian[2000] Mücke et al.[2003]). Blazars presenting the first peak in their SED at UV/X-ray energies (νpeak > 1015 Hz) are referred to as high-synchrotron peaked blazars (HSPs). For intermediate-synchrotron peaked blazars (ISPs), the synchrotron peak frequency lies at 1014 Hz < νpeak < 1015 Hz. Those blazars presenting their synchrotron peak frequency at νpeak < 1014 Hz, between radio and optical wavelengths, are known as low-synchrotron peaked blazars

* Tables B.1, B.2, B.3, B.4 and C.1 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/
(LSPs; Abdo et al. 2010a). BL Lacs can belong to all these three categories, while most FSRQs have been classified as LSPs.

Ghisellini et al. (1998) showed that the SED in blazars is correlated with the bolometric luminosity, forming so-called blazar sequence. As the bolometric luminosity increases, blazars become redder, that is, their two bumps in the SED show smaller peak frequencies and the Compton peak becomes increasingly dominant. Ghisellini et al. (1998) interpret this as a result of the different amounts of radiative cooling suffered by electrons in different sources. On the other hand, Giommi et al. (2012) consider that this blazar sequence is mostly a selection effect due to the selection of sources from radio- and X-ray-flux-limited samples. Using Monte Carlo simulations to populate the blazar sequence, these latter authors consider that BL Lacs could not be plotted at high luminosity and high $\nu_{\text{peak}}$; not because these objects do not exist but rather because it is not possible to measure their redshifts and therefore it is not possible to estimate their luminosities. Ghisellini et al. (2017) used the Third Large-Area telescope AGN Catalogue (3LAC; Ackermann et al. 2015) to revisit the blazar sequence. They constructed their average SED using $\gamma$-ray luminosities, finding an anti-correlation with the synchrotron peak frequency. Their new results support the blazar sequence scenario.

The Fermi Gamma-ray Space Telescope launched in 2008 has revealed more than 5000 sources. With a sky density of $\sim$0.1 sources $\text{deg}^{-2}$, blazars and particularly BL Lacs dominate the $\gamma$-ray sky and constitute more than 75% of the associated sources in all releases of the Fermi catalogues (1FGL, Abdo et al. 2010b), (2FGL, Nolan et al. 2012), (3FGL, Acciari et al. 2015) and (4FGL, Abdollahi et al. 2020). However, all these catalogues present a fraction of about one-third of the sources as unassociated or unknown. The discovery that blazars occupy a narrow region in the WISE IR-colour-colour space, the so-called WISE blazar strip (WBS; Massaro et al. 2011), D’Abrusco et al. (2012), has been used to search for blazar-like sources within the positional uncertainty regions of the unidentified or unassociated $\gamma$-ray sources (UGSs) leading to many new blazar candidates (D’Abrusco et al. 2014, 2019, Alvarez Crespo et al. 2016, de Menezes et al. 2020).

Several studies have proven that BL Lacs exhibit high amplitude and rapid variability on timescales that can vary from hours to months, and so the nature of the X-ray spectra in BL Lacs is variable and shows a complex behaviour (see e.g. Zhang et al. 2006, Falcone et al. 2004, Brinkmann et al. 2005). The shape of the X-ray spectrum can provide information that can be used to reveal the emission components, as X-ray emission probably originates in the inner parts of the relativistic jet. The transition in the SED between synchrotron and IC is in BL Lacs located with the X-rays, and therefore characterising the spectra in this band where both processes can contribute to the X-rays is of special relevance. When the mechanism responsible for the emission is synchrotron, we observe a steep power-law energy distribution ($\alpha > 1$, $F \propto \nu^{-\alpha}$) due to the tail of its spectrum, while if IC is the dominant process we observe a flat component ($\alpha < 1$). In the SED of HSPs, the X-ray radiation comes from the high-energy end of the synchrotron, whereas in LSPs it comes from Compton scattering.

Here we present a catalogue that compiles 310 observations corresponding to 103 different BL Lacs observed with XMM–Newton over nearly 20 years of operations. We make use of the fifth edition of the catalogue Roma-BZCAT (‘BZCAT’ hereafter, Massaro et al. 2015), which constitutes the most comprehensive list of blazars known to date and is based on multi-frequency surveys and information reported in the literature. BZCAT contains 3561 sources, of which 1151 are confirmed BL Lacs. Here we report those BL Lacs observed by XMM–Newton and reported in the archival public observation up to September 2019. We fit six different models to each XMM–Newton source where sufficient counts are available to produce a spectrum: two different phenomenological models, log parabola and power law, each with three different flavours for the absorbing column density. We study their parameters and choose the best-fit model. The catalogue includes light curves, derived variability parameters, and optical and ultraviolet (UV) information when available.

The paper is organised as follows. In Sections 2 and 3 we describe the sample selection with observations and data analysis, respectively. In Section 4, we describe the catalogue, the products and how to access it. In Section 5 we present and discuss the spectral properties and the results of the best-fit model, and in Section 6 we present our conclusions.

Unless otherwise stated, we assume a flat $\Lambda$CDM cosmology with a Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, total matter density $\Omega_m = 0.27$ and dark energy density $\Omega_{\Lambda} = 0.73$. Magnitudes throughout this paper refer to the AB magnitude system (Oke 1974).

2. Sample selection

The sample we present here is the result of a cross-correlation between the 1151 BL Lac subsample given in the fifth version of the Roma–BZCAT and all the pointed science public observations available in the XMM–Newton archive. Overall, observations covered by the catalogue include the period from March 2000 to September 2019. Calibration observations cover up to September 2020. Their cross-correlation with the XMM–Newton archive yields a total of 310 XMM–Newton observations that contain a BZCAT source, corresponding to 103 different BL CAT sources. The 310 XMM–Newton observations are selected by searching in squares of sizes $S_\alpha = 0.5^\circ$/$\cos(\text{Dec})$, $S_\nu = 0.5^\circ$, centred at the positions of the BZCAT sources to see if the centre of an XMM–Newton observation is contained within this box, which is equivalent to saying that the BZCAT source is contained within any field of view of an XMM–Newton observation. Figure 1 shows the sky distribution in equatorial coordinates of the BZCAT BL Lacs and those present in our XMM–Newton BL Lac Catalogue. Because of the selection procedure, the sample is heterogeneous, certainly not complete, and sources are observed in different epochs.

In the XMM–Newton BL Lac catalogue, 101 of the 103 different sources are detected in the EPIC cameras (EPIC-MOS and EPIC-pn, respectively) as described in Section 3. The BL Lac 5BZB2124+0020 (1/103) is detected in one pointing and undetected in another. For the remaining (2/103) BL Lacs, flux upper limits are provided. The BL Lacs detected in our catalogue are a combination of XMM–Newton targets (41/101) and serendipitous objects (60/101) found anywhere within the field of view of the EPIC cameras. Within the 41 sources that are targets, 4 sources are the target of observations in some observations and field sources in other observations. Any source lying more than 0.5 from the nominal XMM–Newton pointing is considered serendipitous. All calibration sources are considered as targets, even if displaced from the nominal pointing.

We classify the BL Lacs according to the estimated value of the synchrotron peak frequency $\nu_{\text{peak}}$ calculated in the ob-
I. de la Calle Pérez, N. Álvarez Crespo, E. Racero & A. Rouco: An XMM–Newton catalogue of BL Lacs

Fig. 1: Equatorial coordinates of the BL Lacs from BZCAT, indicated as black points. Red crosses mark the distribution of those sources contained in the catalogue of XMM–Newton BL Lacs.

served frame as defined in Section 4, following the nomenclature used in the Fourth Large-Area Telescope AGN Catalogue (4LAC, Ajello et al. 2020). For some BL Lacs these values are reported in the 4LAC, while for the rest of the sources we build their SEDs source by source using the ASDC SED Builder Tool 2, which collects all available data in the literature. We estimate the peak of the synchrotron emission $\nu_{\text{peak}}$ using a third-degree polynomial fit on the low-energy hump:

$$\log (\nu F_\nu) = A (\log \nu)^3 + B (\log \nu) + C,$$

where the error associated with $\log \nu_{\text{peak}}$ is typically ~0.5 due to the use of non-simultaneous broadband data (Kapanadze 2013).

With this criteria, about 48% of the BL Lacs in the XMM–Newton catalogue are classified as HSPs, 26% as ISPs, and 21% as LSPs. For the remaining fraction of sources, it is not possible to make a classification because of a lack of sufficient broadband data to perform an adequate fit.

3. Observations and data analysis

3.1. Instrument and observations

The XMM–Newton observatory carries several coaligned X-ray instruments: the European Photon Imaging Camera (EPIC) and two reflection grating spectrometers (RGS1 and RGS2, Jansen et al. 2001). The EPIC cameras consist of two metal-oxide semiconductors (EPIC-MOS, Turner et al. 2001) and one pn junction (EPIC-pn, Strüder et al. 2001) CCD array, which have a ~30’ field of view (FOV) and can offer 5 - 6’ spatial resolution and 70 - 80 eV energy resolution in the 0.2 - 10 keV energy band. XMM–Newton also has a co-aligned optical/UV telescope of 30 cm in diameter (Optical Monitor, OM), providing strictly simultaneous observations with the X-ray telescopes (Mason et al. 2001). It has three optical and three UV filters, with effective wavelengths: V: 543 nm, B: 450 nm, U: 344 nm, UVW1: 291 nm, UVM2: 231 nm, and UVW2: 212 nm covering a $17 \times 17$ arcmin$^2$ FOV (but with the actual imaged sky area being dependent on the user-chosen mode) and a point spread function (PSF) of less than 2” FWHM —depending on filter— over the full FOV (Rosen 2020).

The information on the 310 XMM–Newton observations reported in this work comes mainly from the EPIC detector. EPIC observations present in this catalogue have been taken under timing and imaging mode, this latter in combination with different window modes (Small Window, Large Window, and Full Frame) and filters (Thick, Medium, and Thin). EPIC data are available for all observations in at least one of the three cameras. For 35% (36/103) of the objects, several observations exist. Observing times per observation range between 2.7 ks and 144 ks (see Fig. 2), and observing times per object range between 2.7 ks and 2.2 Ms, spanning several years in some cases.

Data provided by the OM exist for 45% (46/103) of the objects in at least one of the filters. For 8 objects, data exists in all six filters (three optical and three UV). For 12 objects, there are data in all three optical filters, and for 13 there are data in all three UV filters. For 26 objects there are data in at list one optical and one UV filter. For 5 objects, no OM data are available due to the presence of bright objects in the field of view.

The following sections describe the EPIC data-reduction procedure.

3.2. Data reduction

The XMM–Newton observatory carries several coaligned X-ray instruments: the European Photon Imaging Camera (EPIC) and two reflection grating spectrometers (RGS1 and RGS2, Jansen et al. 2001). The EPIC cameras consist of two metal-oxide semiconductors (EPIC-MOS, Turner et al. 2001) and one pn junction (EPIC-pn, Strüder et al. 2001) CCD array, which have a ~30’ field of view (FOV) and can offer 5 - 6’ spatial resolution and 70 - 80 eV energy resolution in the 0.2 - 10 keV energy band. XMM–Newton also has a co-aligned optical/UV telescope of 30 cm in diameter (Optical Monitor, OM), providing strictly simultaneous observations with the X-ray telescopes (Mason et al. 2001). It has three optical and three UV filters, with effective wavelengths: V: 543 nm, B: 450 nm, U: 344 nm, UVW1: 291 nm, UVM2: 231 nm, and UVW2: 212 nm covering a $17 \times 17$ arcmin$^2$ FOV (but with the actual imaged sky area being dependent on the user-chosen mode) and a point spread function (PSF) of less than 2” FWHM —depending on filter— over the full FOV (Rosen 2020).

The information on the 310 XMM–Newton observations reported in this work comes mainly from the EPIC detector. EPIC observations present in this catalogue have been taken under timing and imaging mode, this latter in combination with different window modes (Small Window, Large Window, and Full Frame) and filters (Thick, Medium, and Thin). EPIC data are available for all observations in at least one of the three cameras. For 35% (36/103) of the objects, several observations exist. Observing times per observation range between 2.7 ks and 144 ks (see Fig. 2), and observing times per object range between 2.7 ks and 2.2 Ms, spanning several years in some cases.

Data provided by the OM exist for 45% (46/103) of the objects in at least one of the filters. For 8 objects, data exists in all six filters (three optical and three UV). For 12 objects, there are data in all three optical filters, and for 13 there are data in all three UV filters. For 26 objects there are data in at list one optical and one UV filter. For 5 objects, no OM data are available due to the presence of bright objects in the field of view.

The following sections describe the EPIC data-reduction procedure.

3.2. Data reduction

Our sample has been uniformly analysed using the XMM–Newton standard Science Analysis System (SAS, v18.0.0; Gabriel et al. 2004) and most updated calibration files. Different observations of the same source are not combined for any purposes, including source detection. If several exposures ex-

---

2 See https://tools.ssdc.asi.it/SED
ist for any given observation of a source, then the one with the longest exposure time is used. Event lists are produced for the three EPIC cameras following the standard SAS reduction procedure. Periods of high-background activity are removed following the standard method (Lumb et al. 2002), that is, monitoring the rate of events with pattern '0' and energies >10 keV (the limits that define the good time intervals (GTIs) are defined by background rates EPIC-pn$_{\text{rate}}$ < 1.0 cts/sec and EPIC-MOS$_{\text{rate}}$ < 0.8 cts/sec).

EPIC-MOS1 exposures taken in TIMING mode contained in our data sample are discarded and not used in our analysis. Details explaining why this is the case can be found in the EPIC Status of Calibration and Data Analysis; latest update Oct 2019 (Smith 2019).

We use the standard omichain SAS task to analyse OM data. The processing chain performs source detection and computes rates and instrumental magnitudes as well as fluxes for every source detected.

In the following sections we highlight the main analysis steps needed to go from EPIC source detections (3.2.1), through coordinate corrections (3.2.2), and source cross-match (3.2.3) to end with the extraction of the catalogue products (3.2.4).

3.2.1. Source detection

The source-detection algorithm is applied only to exposures taken in IMAGING mode. If the exposure time is less than 100 secs in any given EPIC exposure after GTI filtering, the exposure is not considered for source detection and the source is flagged as not detected. All the TIMING exposures in our data sample contain a source, so they are flagged as detections by default.

The GTI-filtered event-detection criteria have to be established for the EPIC cameras. For this purpose, images with a bin size of 40 pixels/bin are produced in five different energy ranges (EPIC-pn: 300 - 500, 500 - 2000, 2000 - 4500, 4500 - 7500, 7500 - 12000 eV; EPIC-MOS: 200 - 500, 500 - 2000, 2000 - 4500, 4500 - 7500, 7500 - 12000 eV). These images are used by the SAS task edetect_chain to establish source detection. This task is run simultaneously over the five energy bands and each camera independently. A positive detection requires a detection likelihood threshold of 10. A radial statistical error is associated to every detected source, computed as \(\sqrt{\text{RA}_{\text{err}}^2 + \text{DEC}_{\text{err}}^2}\), where RA$_{\text{err}}$ and DEC$_{\text{err}}$ are the 1\(\sigma\) statistical uncertainties in the derived RA and DEC coordinates respectively.

3.2.2. Source position rectification

Subsets of objects within the XMM–Newton FOV, extracted from large astrometric reference catalogues, are used to rectify the source positions derived by edetect_chain. Before this is done, the SAS task srcmatch is used to create a unique EPIC source list using information from all EPIC cameras in which the source has been detected. This unique list contains average source information, such as fluxes. Within this unique list, the associated RA and DEC are an average of those found independently for each camera, and the positional error is a combination of statistical and systematic errors. For reference, the average 1\(\sigma\) positional error for the whole Fourth XMM–Newton Serendipitous Source Catalogue (4XMM, Webb et al. 2020) is better than \(\sim 1.7''\), with a standard deviation of 1.4. As for the systematic errors, the relative astrometry within each camera is accurate to within 1.5'' over the full FOV.

The SAS task catcorr is run over the unique EPIC source list to update the sky coordinates by cross-matching them with up to three reference external catalogues, (i) the USNO B1 catalogue (Monet et al. 2003), (ii) the 2MASS catalogue (Skrutskie et al. 2006), and (iii) the SDSS (DR9) catalogue (Ahn et al. 2012), to find optical or infrared (IR) counterparts and to find the small frame shifts or rotations that optimise the match. If sufficient matches are found within the FOV to optimise the correction, these shifts are then applied to the positions of all the EPIC sources in the field. The average 1\(\sigma\) field correction is of the order of 2.5''. When catcorr fails to obtain a statistically reliable result, the associated systematic error is assumed to be 1.5''.

The average (over all EPIC cameras) and external catalogue rectified sky coordinates are used as the coordinates of the XMM–Newton X-ray sources that make up our catalogue. The catalogue includes the coordinates XMM_RA, XMM_DEC, XMM_RADEC_ERR, and XMM_RADEC_ERR_CORR before astrometric rectification, and XMM_RA, XMM_DEC, and XMM_RADEC_ERR after astrometric rectification. Two further columns in the catalogue, AstCorr and PosCorr, identify if astrometric rectification has been applied and if the fitting was successful in providing updated coordinates.

3.2.3. Catalogue cross-match

Once we have the XMM–Newton sources with rectified positions, a positive match with a BZCAT source is considered if:

\[
\frac{\text{distance}}{\sqrt{\sigma_{\text{BZCAT}}^2 + \sigma_{\text{XMM}}^2}} \leq 2\sigma,
\]

where distance refers to the distance between the XMM–Newton and BZCAT source in units of arcsec; \(\sigma_{\text{BZCAT}}\) is the reported positional uncertainty of the order of 1''\(\sigma\); and \(\sigma_{\text{XMM}}\) the estimated XMM–Newton positional uncertainty, a combination of \(\sigma_{\text{XMM}} = \sqrt{\sigma_{\text{STAT}}^2 + \sigma_{\text{SYS}}^2}\), the statistical and systematic uncertainty in the XMM–Newton position, where \(\sigma_{\text{STAT}} = 1.5''\) on average, and \(\sigma_{\text{SYS}} \sim 1.5''\). This translates to an average distance no greater than \(\sim 5'' (2\sigma)\) between the XMM–Newton detected source and the BZCAT source in order to consider the X-ray source a match of the BZCAT one.
In summary, if the XMM–Newton detected source is within ~5” of the BZCAT one, we consider the X-ray source to be a positive match. With this criteria, the cross-match yields 307/310 XMM–Newton observations with an identified BZCAT source, corresponding to 103 different BZCAT sources.

3.2.4. Catalogue product extraction

Once a positive identification of the X-ray source has been established, source and background extraction regions are defined to derive source light curves and spectra.

For IMAGING mode, the source region is chosen to be circular around the source centroid with a minimum radius of 20” and limited to a maximum of 40”, whereas the background region is an annulus around the source region with inner radius \( r_{\text{min}} = 60” \) and outer radius \( r_{\text{max}} = 120” \). This selection ensures that the source region is greater than the PSF of the instrument (4 - 6”) and that the background region is away from any possible source contamination. Additional X-ray sources in the background region are masked out by removing those with a detection likelihood greater than 50. The SAS task `eregionanalyse` is used to maximise the S/N calculated from the source counts, the encircled energy fraction, and the background counts to give the optimum source radius and source centroid. If `eregionanalyse` cannot find an optimal extraction radius, the exposure is discarded by our analysis.

An exception to the above rule for IMAGING mode exposures is the definition of background extraction regions taken from exposures in Small Window mode. To avoid contamination from the bright central source, for EPIC-pn the background region is taken from a circular region from a corner of the available window rather than from an annulus around the source. The circular background-extraction region has a radius of 37.5”.

For EPIC-MOS, the background is taken from a circular region from one of the outer CCDs, in particular from CCD5. The radius of the background-extraction region is 120”. Figure 3 illustrates how extraction regions are selected for the two IMAGING mode EPIC exposures, Full Frame and Small Window.

For TIMING mode exposures in EPIC-pn, both source and background are extracted from boxes in RAWX versus RAWY. The source region is defined from a box of 16 × 199 RAW X,Y units with centre \( X_{\text{centre}} = <\text{RAWX}> \) and \( Y_{\text{centre}} = 101 \). The background is extracted from a box of 16 ×199 RAW X,Y units with centre \( X_{\text{centre}} = 8.5 \) and \( Y_{\text{centre}} = 101 \). The background box is moved along RAWX from the edge of the detector by 0.5 units.

For TIMING mode exposures in EPIC-MOS, the source and background are extracted from boxes in RAWX versus TIME. The source region is defined from a box of 60 RAWX units and full time (Exposure) interval with centre \( X_{\text{centre}} = <\text{RAWX}> \) and \( Y_{\text{centre}} = T_{\text{Start}} + <\text{Exposure}>/2 \). The background is extracted from a box of 20 RAWX units with centre \( X_{\text{centre}} = 264.0 \) and \( Y_{\text{centre}} = T_{\text{Start}} + <\text{Exposure}>/2 \), where \( T_{\text{Start}} \) is the exposure start time.
3.2.5. Pile-up evaluation and correction

For IMAGING mode exposures, the presence of ‘pile-up’ is evaluated. To test for pile-up we derived the source + background count rate extracted from a circle around the source of 60″ (this radius contains about 95% of the PSF). To establish the presence of pile-up, these count rates are compared against pile-up limits given in Table 2 of Jethwa et al. (2015) which are in line with the following criteria: a conservative limit where 2% - 3% flux loss and less than 1% spectral distortion is incurred, and a tolerant limit allowing for 4% - 6% flux loss and 1% - 1.5% spectral distortion. These limits are a function of the EPIC observing submodes and are available for Full Frame, Large Window, and Small Window modes, both for EPIC-pn and EPIC-MOS. If the submode is outside these values, a tag UNK is used to mark in the catalogue the presence of pile-up. The number of IMAGING mode exposures in the catalogue where pile-up is present

3% flux loss limit. This is only done to extract spectral products. However, rather than throwing out the exposure, spectral products are still derived from the full source region, and so care has to be taken in interpreting the spectral results derived from these exposures. Overall, the pile-up correction worked for 54 EPIC-pn exposures, 56 EPIC-MOS1 exposures, and 67/114 EPIC-MOS2 exposures where pile-up was present. Table 4 collects the list of 53 observations where there is at least one exposure where pile-up could not be removed. Of these, 25 observations contain no exposures free of pile-up, where 24 of these 25 correspond to observations of MRK 421 (5B2B1110+4+3812). In the remaining 28, it is possible to find at least one exposure that is free of pile-up. In summary, out of the 310 observations contained in the catalogue, 25/310 suffer from irrecoverable pile-up effects.

3.2.6. Quality flags

Several quality flags are checked before catalogue products are extracted. First, we check whether the GTI filtered exposure time is greater than 100 s; if it is not, the analysis of the exposure stops here. If there is a positive detection, the next step is to establish the presence of pile-up, and if present, whether it can be corrected as described in Section 3.2.5. For the light-curve generation, a minimum of 500 s is required. Finally, the spectrum has to contain at least 300 counts to ensure a minimum quality spectral fitting.

3.3. Catalogue products

The catalogue products include EPIC images, light curves, and spectral products. These are obtained from the GTI-filtered event lists as described in Section 3.2. Light-curve and spectral products are acquired from the source- and background-extraction regions as described in Section 3.2.4. When available, OM images together with magnitudes and fluxes are given too. All products have been visually screened to check for problems. In the following sections, we describe how individual products are obtained.

3.3.1. Image generation

Images are produced for all individual IMAGING mode exposures in sky coordinates with a bin size of 40 units. These images are used for source detection and are available in five energy ranges (EPIC-pn : 300 - 500, 500 - 2000, 2000 - 4500, 4500 - 7500, 7500 - 12000 eV; EPIC-MOS: 200-500, 500 -2000, 2000 - 4500, 4500 - 7500, 7500 - 12000 eV). Thumbnail true colour images are produced around the X-ray source, as seen in Fig. 4 (Events in red: 0.5 - 4.5 keV, green: 4.5 - 7.5 keV, blue: 7.5 - 12.0 keV).

3.3.2. OM image and source information

OM images and source information are obtained via the SAS task omichain when OM exposures are available. This SAS perl script reduces OM Imaging mode data and produces individual mosaiced sky images and combined source lists with flux and magnitude information. For the purpose of this work, omichain is run with the optional parameters processmosaicimages and usecat set to true in order to maximise the astrometric accuracy of the detected sources and provide the deepest level of imaging product (mosaiced sky images) when possible.

omichain comprises a number of SAS tasks. The imaging pipeline first processes the image for individual exposures, producing a set of OM imaging-mode products including the list of detected sources per exposure through the omdetect SAS task. In cases where more than one exposure is available per filter, the ommosaic SAS task generates a mosaic sky image per filter as a combination of the individual exposures. omsrclistcomb then combines the source lists corresponding to the available individual exposures. Finally, ommmerge lists combines all the available source lists for the different filters and produces an associated region file. Source quality flags for OM are one of the outputs of omichain and are included in Table B.3 of the catalogue (see Section 4.7). The main OM information contained in our catalogue is magnitudes and fluxes in any of the six passbands where the source is detected. This information is extracted from the observation source list produced by omichain, which includes the results of the combination of multiple exposures and different extraction apertures. These apertures are used to derive fluxes and are not fixed, but vary between 3″ and 6″. Fluxes provided in our catalogue are not extinction corrected. For a more detailed discussion on apertures used to extract fluxes and how to deal with extinction corrections we refer the readers to Page et al. (2012). For the astrometric corrections of the detected sources, omsrclistcomb identifies if USNO catalogue file is available, and if so corrects the astrometry —depending on whether there are sufficient matches of OM detections with USNO objects—in order to account for any offset between the OM and USNO source adding the columns RA_CORR and DEC_CORR to the combined master source list. This final list is then cross-matched with the coordinates of our source of interest. We follow the same procedure as described in 3.2.3 for the EPIC cameras. In this case, we consider $\sigma_{\text{MM,OM}} = (\sigma_{\text{STAT}}^2 + \sigma_{\text{SYS}}^2)$ the estimated positional uncertainty, a combination of statistical and systematic uncertainties in the OM position, where $\sigma_{\text{STAT}}$ ranges from 0.05 to 2.57″, with a mean position uncertainty of 0.68″ (Page et al.)
Table 1: List of 53 observations with at least one EPIC exposure where pile-up is present and cannot be corrected.

| BZCAT Object       | Observation ID | EPIC-pn | EPIC-MOS1 | EPIC-MOS2 |
|--------------------|----------------|---------|-----------|-----------|
| 5BZBJ1104+3812     | 0158971201     | NO      | YES       | YES       |
|                    | 0136541001     | NO      | YES       | YES       |
|                    | 0099280101     | NO      | YES       | YES       |
|                    | 0658800101     | YES     | YES       | YES       |
|                    | 0136540901     | YES     | YES       | YES       |
|                    | 0158970101     | NO      | NO        | YES       |
|                    | 0411082701     | YES     | YES       | YES       |
|                    | 0560983301     | YES     | YES       | YES       |
|                    | 0411083201     | YES     | YES       | YES       |
|                    | 0653630801     | YES     | YES       | YES       |
|                    | 0658801301     | YES     | YES       | YES       |
|                    | 0099280201     | NO      | YES       | NO        |
|                    | 0153950701     | YES     | YES       | YES       |
|                    | 0136540801     | YES     | YES       | NO        |
|                    | 0510610201     | NO      | YES       | YES       |
|                    | 0411081901     | NO      | YES       | YES       |
|                    | 0560980101     | YES     | YES       | YES       |
|                    | 0136541201     | YES     | YES       | YES       |
|                    | 0658802301     | NO      | YES       | YES       |
|                    | 0411080301     | YES     | YES       | YES       |
|                    | 0099280301     | YES     | YES       | YES       |
|                    | 0153950601     | YES     | NO        | YES       |
|                    | 0411081301     | YES     | YES       | YES       |
|                    | 0411081401     | YES     | YES       | YES       |
|                    | 0411081501     | YES     | YES       | YES       |
|                    | 0653630101     | YES     | YES       | YES       |
|                    | 0653631301     | YES     | YES       | YES       |
|                    | 0791780601     | YES     | YES       | YES       |
|                    | 0411081601     | YES     | YES       | YES       |
|                    | 0136540101     | YES     | YES       | YES       |
|                    | 0099280401     | YES     | NO        | NO        |
|                    | 0136540701     | YES     | YES       | YES       |
|                    | 0810860201     | YES     | YES       | YES       |
|                    | 0658801801     | NO      | YES       | YES       |
|                    | 0091470101     | YES     | YES       | YES       |
|                    | 5BZBJ1136+7009  | 011140101 | NO     | NO        | YES       |
|                    | 5BZBJ1221+3010  | 0300140101 | NO     | YES       | YES       |
|                    | 5BZBJ1428+4240  | 0111850201 | NO     | NO        | YES       |
|                    | 5BZBJ1653+3945  | 0652570201 | NO     | YES       | YES       |
|                    | 5BZBJ1959+6508  | 0850980101 | NO     | YES       | YES       |
|                    | 5BZBJ2158+3013  | 0124903001 | NO     | YES       | NO        |
|                    | 5BZBJ2359+3037  | 0693500101 | NO     | YES       | YES       |
|                    | 0722286001     | NO      | YES       | NO        |

Column description: (1): Source name as given in BZCAT, (2): XMM–Newton Observation ID, (3): flag indicating whether EPIC-pn is affected by pile-up, (4): idem EPIC-MOS1 and (5): idem EPIC-MOS2.

$\sigma_{\text{SYS}} \sim 0.7''$ (Rosen 2020). In a similar manner as with EPIC sources, this implies that a significant positive match is found if the BZCAT source lies within $\sim 3''$ of the OM source. This is a purely geometrical approach based on the statistical co-ordinates of the OM source and no attempt has been made to use the extent of the OM source. The observation source lists contain information relative to the extension of the source. This information is not contained in our catalogue.
3.3.3. Light-curve generation

Source and background light curves are produced in two energy ranges, $E_{\text{soft}} = 0.2 - 2.0$ keV and $E_{\text{hard}} = 2.0 - 10.0$ keV, over bins of 500 s. For TIMING mode exposures, the low-energy limit of the soft band light curve is set at 0.3 keV to avoid low-energy noise.

The SAS task epiclccorr is used to produce background-subtracted source light curves corrected for inefficiencies of the instrument (vignetting, chip gaps, PSF etc.) and time corrections (dead time, GTIs, etc.). A hardness ratio ($E_{\text{hard}}/E_{\text{soft}}$) light curve is also produced. The left panel in Fig. 5 shows a representative example of a generated light curve. Weighted average rates over the entire exposure are identified (marked in red) and not used in the calculation of these average rates.

3.3.4. X-ray variability

We measure and quantify the source X-ray variability using the above-generated light curves for each exposure separately and over the two defined energy ranges ($E_{\text{soft}} = 0.2 - 2$ keV and $E_{\text{hard}} = 2 - 10$ keV). For both, we use the SAS task ekstest. The task uses the source and background time series to run several variability tests. Only bins within GTI intervals are used and bins containing null or negative values are eliminated.

The $\chi^2$ analysis is used to test the null hypothesis of a constant source rate, so that sources are reported as variable in Table C.1 when the $\chi^2$ probability is $\leq 10^{-5}$ in at least one exposure (Rosen et al. 2016). Both quantities, $\chi^2$ and $\chi^2$ probability, are included in the catalogue for every EPIC exposure and each energy range ($E_{\text{soft}}$ and $E_{\text{hard}}$).

In addition, to quantify the scale of the variability, we use the fractional root mean squared variability amplitude $F_{\text{var}}$ (Nandra et al. 1997; Vaughan et al. 2003). This variable is the square root of the excess variance after normalisation by the mean count rate $\bar{x}$. This is used as an estimator of the intrinsic source variance and is defined as:

$$F_{\text{var}} = \sqrt{\frac{\chi^2}{\bar{x}^2} - \sigma_{\text{err}}^2},$$

(3)
where $S^2$ is the variance of the time series with N bins,

$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2,$$  

(4)

and $\sigma_{\text{err}}^2$ is the mean square error of the time series. $F_{\text{var}}$ can be expressed as a percentage. The uncertainty in $F_{\text{var}}$ takes the form:

$$\Delta F_{\text{var}} = \frac{1}{2F_{\text{var}}} \left[ \left( \frac{2 \sigma_{\text{err}}^2}{N \bar{x}^2} \right)^2 + \left( \frac{\sigma_{\text{err}}^2}{F_{\text{var}} \bar{x}} \right)^2 \right].$$  

(5)

Both quantities $F_{\text{var}}$ and $\Delta F_{\text{var}}$ are included in the catalogue for every EPIC exposure and each energy range ($E_{\text{soft}}$ and $E_{\text{hard}}$).

3.3.5. Spectra generation

Source and background spectra are produced in the full energy range (0.2 - 10 keV) with an energy resolution of 5 eV. The SAS task **backscale** is used to calculate the area of the two regions used to extract the spectra. The corresponding response and ancillary files are also created. Finally, the spectra are re-binned in order to avoid oversampling the intrinsic energy resolution of the EPIC cameras by a factor larger than three while making sure that each spectral channel contains at least 25 background-subtracted counts to ensure the validity of Gaussian statistics and hence the applicability of the $\chi^2$ goodness-of-fit test.

3.3.6. Spectral fits

All the spectral fits are performed uniformly over our data sample with the XSPEC package version 12.10.1 (Arnaud 1996). Spectral fits to the time-averaged spectra are performed in the energy range 0.3 - 10 keV in the case of IMAGING mode exposures and 0.6 - 10 keV in the case of TIMING mode exposures. Upper and lower confidence intervals are derived for relevant model parameters at the 68% level. For those fits where $\chi^2_{\text{norm}} > 2.0$, confidence intervals are not derived and instead parameter errors are reported at the 1σ level.

**For all those instruments available within an observation where the source has been detected and passes the quality control flags (Section 3.2.6), we perform spectral fits and derive spectral parameters on an instrument-by-instrument basis and for the combined spectra of all those instruments.**

Within XSPEC, fits are performed using C-statistics, while to test the goodness of fit, that is, how well the statistical model matches the data, $\chi^2$ statistics is used with standard weights (the statistical error given in the input spectrum). All spectra are fitted using the following two baseline models (Perlman et al. 2005):

- **Power law:**

$$N(E) = e^{-\sigma N_H} \cdot K \cdot E^{-\Gamma},$$  

(6)

where $\Gamma$ is the photon index. Within XSPEC, we use the pegpwrlw model, which also allows a simple extraction of the flux at a given energy. In our case, we extract the X-ray flux at 5 keV.

- **Log parabola:**

$$N(E) = e^{-\sigma N_H} \cdot K \cdot (E/E_1)^{-\Gamma - \beta \log(E/E_1)},$$  

(7)

where $\Gamma$ is the photon index and $\beta$ measures the curvature of the parabola. $E_1$ is a scale parameter (always frozen during the fitting procedure) which is set to the lower energy range used for fitting (Massaro et al. 2004). Within XSPEC, the logpar model is used.

Both models are applied using neutral cold absorption ($e^{-\sigma N_H}$) where $N_H$ is the column density and $\sigma$ is the photoelectric cross-section of the process according to Morrison & McCammon (1983). For $N_H$, the following variations are tested:

- $N_H$ fixed to the Galactic column density, $N_{H\text{Gal}}$, during the fitting procedure. $N_{H\text{Gal}}$ has been taken from the HI4PI, a full-sky HI survey based on EBHIS and GASS (HI4PI Collaboration et al. 2016). Within XSPEC, the tbabs model is used.

- $N_H$ is left free to vary during the fitting procedure. Within XSPEC, the tbabs model is used.

- A combination of two $N_H$ values is used, $N_{H\text{Gal}}$ and $N_{H\text{Z}}$. The first fixed to the Galactic column density value during the fitting procedure and the second one used to account for any extra local absorption and left free to vary during the fitting procedure. This extra local component is a function of the source redshift. Within XSPEC, the ztbabs model is used.

Absorbed fluxes and luminosities (when redshifts are available) are derived inside XSPEC over the three bands used (soft, 0.2 - 2.0 keV; hard, 2.0 - 10.0 keV; and full energy band 0.2 - 10.0 keV). The right panel of Fig. 5 shows an example generated spectrum and the results of the combined spectral fit using the model power law with two absorption components, $N_{H\text{Gal}}$ and $N_{H\text{Z}}$.

3.3.7. Flux upper limits

When no X-ray source is detected, flux upper limits at the BZCAT source location are derived over three different energy ranges (soft, 0.2 - 2.0 keV; hard, 2.0 - 10.0 keV; and full energy band 0.2 - 10.0 keV) at the 3σ confidence level. Flux upper limits are first derived in cts/sec from a 30″ radius region around the source location using the SAS task **eregionanalyse** using both a background and an exposure map. Count rates are converted afterwards to flux in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$ using Energy Conversion Factors (ECFs) for each energy range (Mateos et al. 2009). These ECFs are derived from simulations assuming an absorbed power law model with $N_H = 3.0 \times 10^{20}$ hydrogen atoms cm$^{-2}$ and $\text{PhotonIndex} \approx 1.7$. The ECFs used are camera-, energy band-, and filter dependent. When the redshift is available, upper limits to the luminosity are also derived. Only two sources in the catalogue do not show significant X-ray emission, namely 5BZBJ1721+6004 and 5BZBJ2036+6553. The source 5BZBJ2214+0020 is present in two XMM–Newton observations and in one of them (ObsdId 0673000137) no significant emission is detected. Table 2 summarises these results.

4. The catalogue

4.1. Description and access

The full catalogue is divided into four different tables. Tables B.1, B.2, B.3, and B.4 report the description of the contents of
Table 2: List of XMM–Newton observations where no X-ray emission is detected at the location of the BZCAT source.

| BZCAT Object | Observation ID | Flux U.L. $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ | Luminosity U.L. $10^{44}$ erg s$^{-1}$ |
|--------------|----------------|---------------------------------------------|----------------------------------------|
|              |                | (0.2-10 keV)                               | (0.2-2 keV)                            |
| 5BZBJ1721+6004 | 0651371901      | 0.98                                        | 0.31                                   |
| 5BZBJ2036+6553 | 0301651401      | 7.33                                        | 2.69                                   |
| 5BZBJ2214+0020(*) | 0673000137      | 1.60                                        | 0.70                                   |

Column description. (1): Source name as given in BZCAT, (2): XMM–Newton Observation ID, (3): flux upper limit at the 3σ confidence level in the three energy ranges indicated, (4): luminosity upper limits idem. (*) This BZCAT source is detected in XMM–Newton Observation ID 0673000136.

each one, including the column name, units, and a short description of each column.

The first table is named "catalogue", and contains 310 rows, one for each unique XMM–Newton observation, each characterised by an observation ID (ObsId) and 148 columns (Table B.1). Here, for each individual EPIC camera within an observation, we report different exposure and analysis properties, such as analysis quality flags (section 3.2.6), source position rectification (section 3.2.2), detection flags (section 3.2.1), pile-up and pile-up-correction flags (section 3.3.5), fit statistics (section 3.3.6), and flags to check whether light curves and spectral products are extracted (sections 3.3.3 and 3.3.5). The table also reports some source properties, such as count rates and variability parameters as defined in section 3.3.4, also the flux extracted at 5 keV, the total flux, and the luminosity in the entire, soft, and hard energy bands extracted from the combined EPIC fit for the model power law with two absorption components (section 3.3.6). Finally, detection flags and OM magnitudes and fluxes in the available filters are included (section 3.3.2).

The next table of the catalogue of XMM–Newton BL Lacs is named "model" and reports information on the fits to the individual and combined EPIC exposures. The table contains 7440 rows and 62 columns as described in Table B.2. Here we report the best-fit model parameters obtained from the spectral fits (section 3.3.6). The model table also includes background-subtracted counts (section 3.3.3) and pile-up information (section 3.3.5). For each ObsId, there are six rows corresponding to the results of the fits for the six different models and for each one of the three EPIC instruments (a total of 18 rows). The table also includes six rows, one for each of the six different models, for the results of the combination of spectra for all the EPIC instruments for which there is a valid spectra. The combined spectral fit results are reported as "epic" under the Inst column of the table. In summary, for each unique observation (ObsId) there are 24 rows (6 models for each one of the three EPIC instruments plus their combination).

The third extension is "auxdata" and contains 310 rows, one for each ObsId and 53 columns with auxiliary data. These include cross-matched source information, product-extraction regions (source and background), pile-up-correction regions, EPIC light curve start and end time, light-curve time bin, and OM source quality flags (section 3.3.2). The description for these columns is reported in Table B.3.

The last table from the catalogue of XMM–Newton BL Lacs is called "multiqref", contains 92 rows and 45 columns, and is described in Table B.4. This table reports the non-biased ObsIds that correspond to 79 different BL Lacs selected as reported in Section 5.3. This set of observations is used to study the average spectral properties of the sample. The spectral information included in the table comes from the model log parabola with $N_H$ free. This table also combines this information with multi-frequency information as explained in section 4.2.

In Table C.1 we present a "slim" version of the source catalogue. The slim version includes one entry per source in the catalogue (103) and information on some source properties, including BL Lac name and coordinates taken from BZCAT, redshift, galactic column density from the HI4PI Collaboration et al. (2016), the cumulative XMM–Newton exposure time available per each BL Lac and the number of observations available in the XMM–Newton archive (XSA) for each BL Lac is also included. Those BL Lacs that are not the target of an XMM–Newton observation but rather found in the FOV are indicated by a symbol. We also include a flag indicating whether the light curve and spectra are produced. Additionally, we report the SED classification, the logarithm of the synchrotron peak in observed frame as indicated in Section 2 and a flag indicating whether the source is variable in the soft and hard bands as described in Section 5.3. Finally, some multi-wavelength information is included, such as the name of the 4FGL catalogue association and a flag indicating whether there is an association in the TeVCat.

The full catalogue is provided in a series of Flexible Image Transport System (FITS) files with extension names: "catalogue", "model", "auxdata", and "multiqref", corresponding to the tables described above. The catalogue of XMM–Newton BL Lacs can be found at VizieR+ and will also be available through ESASK+.

4.2. Multi-wavelength information

As BL Lacs are the most numerous extragalactic γ-ray emitters, we have cross-matched our catalogue of XMM–Newton BL Lacs with the 4FGL (Abdollahi et al. 2020) to search for γ-ray counterparts. A BL Lac from our catalogue is considered to be associated with a 4FGL source when their angular distance is equal to or smaller than the semi-major axis of the 95% error ellipse for the position of the 4FGL source.

About 61% (63/103) of the XMM–Newton BL Lacs are present in the 4FGL, so they are strong γ-ray emitters. The table multiqref includes the associated 4FGL source name, the photon flux between 1 and 100 GeV (Flux_1000), the energy flux between 100 MeV and 100 GeV (Energy_Flux1000), the variability index (Variability_Index_4FGL), and the fractional variability (Frac_Variability_4FGL).

Moreover, we report the associations with the TeVCat3 version 3.4 updated up to March 2021, which is an online catalogue for TeV astronomy. For the identification, we used

3. https://vizier.u-strasbg.fr
4. https://sky.esa.int
5. http://tevcat.uchicago.edu
the same angular distance as for the 4FGL. About 17.5% (18/103) of the XMM–Newton BL Lacs have associated TeV emission.

Additionally, we report associations with several radio catalogues. The radio flux density at 1.4 GHz is selected, performing a cross-match with the latest version of the radio catalogue NRAO VLA Sky Survey (NVSS, Condon et al. 1998), as well as that at 845 MHz from the latest release of the Sydney University Molonglo Sky Survey Source catalogue (SUMSS, Mauch et al. 2003). All the cross-matches are performed establishing a search radius of 10" (Galdiati et al. 2005).

4.3. Calibration sources

Several of the sources included in our catalogue are—or were—4.3. Calibration sources

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%

Several of the sources included in our catalogue are —or were—

search radius of 10" (Galbiati et al. 2005). About 17.5%
In order to determine which spectral model best fits the data, we use the fit results from the combination of the EPIC detectors, indicated as “epic” in column Inst of Table B.2, which are free or successfully corrected for pile-up. For every single observation, this can be any combination of one, two, or three EPIC cameras. This leaves a total of 218 observations, which are used to extract results for each one of the six available models. The power law and log parabola models with the different flavours of $N_H$ are fitted uniformly to the entire sample. The goodness of fit is evaluated using $\chi^2$ statistics. Figure 7 presents a box plot of the distribution of $\chi^2$ for the six models applied and described in Section 3.5.6. This type of plot is a non-parametric method for graphically representing variation in samples of a statistical population without making any assumptions as to the underlying statistical distribution. These plots show the median, the lower (Q1, 25%) and upper (Q3, 75%) quartiles, the minimum and maximum values after excluding possible outliers (indicated in the figure by the stars), and outliers (indicated in the figure by the whiskers), the confidence interval (represented as 1.5× (Q3 - Q1) and indicated in the figure by the boxes).
Continuation, list of XMM–Newton calibration observations included in the catalogue.

| BZCAT Object         | Observation ID | RA Nom. | Dec Nom. | Revolution | Obs. Start | Obs. Duration |
|----------------------|----------------|---------|----------|------------|------------|--------------|
| 5BZBJ2158-3013       | 0124930901     | 21 58 52.06 | -30 13 32.1 | 480        | 2002-05-29 20:17:21.0 | 104968       |
|                      | 0124930601     | 21 58 52.06 | -30 13 32.1 | 545        | 2002-11-20 23:27:28.0 | 114675       |
|                      | 0158960101     | 21 58 52.06 | -30 13 32.1 | 724        | 2003-11-23 00:46:22.0 | 27159        |
|                      | 0158960901     | 21 58 52.06 | -30 13 32.1 | 908        | 2004-11-22 21:35:30.0 | 28919        |
|                      | 0158961001     | 21 58 52.06 | -30 13 32.1 | 908        | 2004-11-23 19:45:55.0 | 40419        |
|                      | 0158961101     | 21 58 52.06 | -30 13 32.1 | 993        | 2005-08-12 21:51:06.0 | 28930        |
|                      | 0158961301     | 21 58 52.06 | -30 13 32.1 | 1095       | 2005-11-30 20:34:03.0 | 60415        |
|                      | 0158961401     | 21 58 52.06 | -30 13 32.1 | 1171       | 2006-05-01 12:55:55.0 | 64814        |
|                      | 0411780101     | 21 58 52.06 | -30 13 32.1 | 1266       | 2006-11-07 00:22:47.0 | 101012       |
|                      | 0411780201     | 21 58 52.06 | -30 13 32.1 | 1349       | 2007-04-22 04:07:23.0 | 67911        |
|                      | 0411780301     | 21 58 52.06 | -30 13 32.1 | 1543       | 2008-05-12 19:52:34.0 | 61216        |
|                      | 0411780401     | 21 58 52.06 | -30 13 32.1 | 1734       | 2009-05-28 08:08:42.0 | 64820        |
|                      | 0411780501     | 21 58 52.06 | -30 13 32.1 | 1902       | 2010-04-28 23:47:42.0 | 74298        |
|                      | 0411780601     | 21 58 52.06 | -30 13 32.1 | 2084       | 2011-04-26 13:30:40.0 | 63818        |
|                      | 0411780701     | 21 58 52.06 | -30 13 32.1 | 2268       | 2012-04-28 00:48:26.0 | 68735        |
|                      | 0411780801     | 21 58 52.06 | -30 13 32.1 | 2449       | 2013-04-23 22:31:38.0 | 76015        |
|                      | 0727770901     | 21 58 52.09 | -30 13 32.1 | 2633       | 2014-04-23 05:14:56.0 | 65000        |
|                      | 0124931001     | 21 58 53.00 | -30 13 35.0 | 87         | 2000-05-30 29:32:40.0 | 61109        |
|                      | 0124931002     | 21 58 53.00 | -30 13 35.0 | 87         | 2000-05-31 00:30:51.0 | 72558        |
|                      | 0124930101     | 21 58 53.00 | -30 13 35.0 | 362        | 2001-11-03 23:39:00.0 | 92617        |

Column description. (1): Source name as given in BZCAT, (2): XMM–Newton observation ID, (3): right ascension of nominal XMM–Newton pointing, (4): declination of nominal XMM–Newton pointing, (5): revolution number, (6) observation start date and (7): observation duration.

Figure[1] shows that the best models in terms of goodness of fit are both the log parabola with N$_H$ free and the log parabola with two N$_H$ components (N$_{HiGal}$ and N$_{Hi}$). Of the six models tested, the log parabola with N$_H$ free provides the best fit in 71/218 cases, followed by the log parabola with the two N$_H$ components (57/218). The power law model with two absorption components follows (35/218) and then the log parabola fixing N$_H$ (24/218). The power law with N$_H$ free (19/218) and fixing N$_{Hi}$ (12/218) provide the least number of times the best representation of the data. Figure[1] also shows that, on average, log parabola models provide a better fit to the data than power law models, with lower medians and less dispersion of $\chi^2$. A log parabola is favoured in 152/218 of the spectra fitted versus a simple power law which is favoured in 66/218. In terms of N$_H$, using two N$_H$ components (N$_{HiGal}$ and N$_{Hi}$) provides better fits (92/218), while leaving the N$_H$ free to vary during the fitting procedure is favoured in 90/218 spectra and fixing N$_H$ to the N$_{HiGal}$ is favoured in 36/218 spectra.

In Fig.8 we represent the flux distributions in the 0.2 - 10.0 keV band for those sources for which the power law model is preferred and those best fitted by a log parabola (combining all three absorption flavours), and see that those sources favouring a log parabola present significantly higher fluxes. We use a t-test and reject the null hypothesis that the means of both distributions are equal considering different variances with 99% confidence. The fact that the log parabola is preferred for sources that show higher fluxes, that is, sources with higher S/N as in Donato et al. (2005), might indicate that curvature is intrinsic to this type of object but only shows when the S/N is sufficiently high.

5.3. Spectral properties

For the following analysis, we only consider the best-fit model log parabola with N$_H$ free, and we exclude from this sample those ObsIds poorly fitted with a value for the $\chi^2$ $>$ 2 and those ObsIds that show pile-up in any of the EPIC cameras (see Table[1]). After filtering, we have 200 ObsIds that correspond to 79 different BL Lacs. To avoid over-representation by sources observed multiple times we adopt the following procedure (Donato et al. 2005).

- For non-variable sources that only show small variations in both photon index and flux in the 0.2 - 10 keV band, that is, $\Delta \Gamma \leq 0.5$ and flux variation of a factor of less than two between maximum and minimum, we use the mean value for all output parameters derived using the log parabola with N$_H$ free model. Given that XSPEC returns asymmetric errors, the mean and its errors are calculated as follows: for each of the 200 ObsIds, we create a Gaussian distribution centred at the parameter’s value and a total dispersion with an amplitude of the asymmetric error, and take a value inside this distribution. We repeat this process 1000 times and choose as the mean parameter the mean of all simulations for each BL Lac.

- For variable sources that show significant photon index and/or flux variations, that is, $\Delta \Gamma > 0.5$ and/or flux variation of a factor of greater than two between maximum and minimum, we consider the observations corresponding to the extreme parameters, so that the source is represented in both states.

The result of this exercise is what we refer to as a non-biased sample and is summarised in the fourth table of the catalogue, named "multispec" as explained in Section[1]. Its columns are reported and described in Table B.4.

We study the model parameters separating them according to BL Lac subpopulations, seeing that the photon index is steepest for ISPs, followed by LSPs, and lastly HSPs (see Table[4]) and its columns are reported and described in Table B.4.

In Fig.9 we study the model parameters separating them according to BL Lac subpopulations, seeing that the photon index is steepest for ISPs, followed by LSPs, and lastly HSPs (see Table[4]) and its columns are reported and described in Table B.4.
5.4. Luminosity

The distribution of the X-ray luminosity in the intervals 0.2 - 10.0 keV, 0.2 - 2.0 keV, and 2.0 - 10.0 keV for the non-biased sample is given in Fig. 10 in the top, middle, and bottom panels, respectively. The peak of the distribution for BL Lacs in the 0.2 - 10.0 keV band falls at $\tilde{L} = 8.33^{+1.07}_{-0.33} \cdot 10^{44}$ erg s$^{-1}$. LSPs are the most luminous BL Lacs in X-rays, where the median values in the 0.2 - 10.0 keV band, are $\tilde{L}_{\text{LSP}} = 11.03$, $\tilde{L}_{\text{HSP}} = 9.58$, and $\tilde{L}_{\text{ISP}} = 2.82$ in units of $10^{44}$ erg s$^{-1}$. This is true for both soft and hard bands.

5.5. Variability

The fraction of BL Lacs reported as variable in either band according to the $\chi^2$ probability of the constancy test is 56/103 (~54%). These sources are mostly HSPs (31), but also there are 9 ISPs and 14 LSPs that are variable, and 5 of them remain unclassified. The peak of the synchrotron emission $v^s_{\text{peak}}$ for variable BL Lacs lies at higher values ($\log v^s_{\text{peak var}} = 15.35$) than for non-variable BL Lacs ($\log v^s_{\text{peak nonvar}} = 14.78$). Additionally, most of the sources that are strong $\gamma$-ray emitters are variable (13/18 TeV sources and 42/63 4FGL sources).

6. Conclusions

This paper presents the XMM–Newton BL Lac catalogue, which comprises a sample of those BL Lacs reported by BZCAT ob-
We report results from a total of 310 observations that contain X-ray spectra around 7000 spectral fits to extract the best-fit model X-ray spectrum as the result of a statistical acceleration mechanism in which the probability of a particle to remain inside an acceleration region decreases as the energy of the particles increases.

The XMM–Newton BL Lac catalogue is intended to be used as a valuable resource to better understand BL Lacs in the X-rays and their correlations with other wavelengths. Incremental releases are planned to augment this catalogue, with continuous efforts made by the astronomical community in discovering new BL Lacs and more observations becoming available in the XMM–Newton archive in coming years. XMM–Newton instruments remain in good health and are expected to continue being operational for several more years.

Acknowledgements. We thank the anonymous referee for her/his insightful comments that led to significant improvements in the paper. IC would like to thank the XMM–Newton SOC and its members for many fruitful discussions. IC would like to acknowledge support by the Torres Quevedo fellowship programme from the Ministerio de Educación y Ciencia Español and from INSA, and to N. Loiseau who proposed this fellowship. NAC is supported by European Space Agency (ESA) Research Fellowships. This work is based on observations with XMM–Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. This research has made use of data archives, catalogues and software tools from the ASDC, a facility managed by the Italian Space Agency (ASI). This research has made use of the NASA/IPAC Extragalactic Database, operated by the Jet Propulsion Laboratory, Caltech, under the contract with NASA, and the NASA Astrophysics Data System Abstract Service.

References

Abdo, A. A., Ackermann, M., Aguilo, L., et al. 2010a, ApJ, 716, 30
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJS, 188, 405
Abdollahi, S., Acero, F., Ackermann, M., et al. 2020, ApJs, 247, 33
Acciari, V. A., Algo, E., Beilicke, M., et al. 2008, ApJ, 684, L73
Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
Ackermann, M., Ajello, M., Atwood, B. W., et al. 2015, ApJ, 810, 14
Aguilo, I., Kirchbaum, T. P., Urengreht, H., et al. 2006, A&A, 456, 117
Aharonian, F., Ackermanian, A. G., Bazer-Bach, A. R., et al. 2006, A&A, 455, 461
Aharonian, F. A. 2000, New A, 5, 377
Ahn, C. P., Alexandre, R., Allende Prieto, C., et al. 2012, ApJS, 203, 21
Ajello, M., Angioni, R., Axelsson, M., et al. 2020, ApJ, 892, 105
Álvarez Crespo, N., Massaro, F., Milisavljevic, D., et al. 2016, A&J, 151, 95
Arnaud, K. A. 1996, in Astronomical Society of the Pacific Conference Series, Vol. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes, 17
Bach, U., Kirchbaum, T. P., Kraus, A., Witzel, A., & Zensus, J. A. 2006, A&A, 452, 83
Blandford, R. D. & Rees, M. J. 1978, Phys. Scr, 17, 265
Brinkmann, V., Papadakis, I. E., Raeth, C., Mimica, P., & Haberl, F. 2005, A&A, 443, 397
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
D’Abrusco, R., Álvarez Crespo, N., Massaro, F., et al. 2019, ApJS, 242, 4
D’Abrasco, R., Massaro, F., Ajello, M., et al. 2012, ApJ, 748, 68
Appendix A: Sources with long cumulative exposure times.

Nineteen BL Lacs in our catalogue have long cumulative exposure times of over 100 ks, as a result of the existence of several of these sources, spread out over several years. Amongst these BL Lacs, eight are serendipitous sources contained in the FOV of XMM–Newton target observations. Most of these eight sources are contained in different samples of objects selected according to different properties. Below we summarise some of their X-ray spectral properties.

5BZJ0057-2212 Of unknown redshift, there are four observations contained in the catalogue (2000, 2002, 2015 and 2016). All observations but one show a weak X-ray source for which it is not possible to extract good-quality spectra. For the observation with best statistics (2015), the optimal fit is provided by a power law model with two absorption components. The photon index is $1.84$ with a flux of $3.24 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2 - 10 keV range. The source shows no sign of variability within the timescale of the observations for the default 500 s bins used.

5BZJ0333-3619 This BL Lac is observed at $z = 0.308$. Twelve observations spanning 2003 - 2013 are included in the catalogue and all but one are best fitted by a log parabolic model. The average flux is about $0.5 - 3.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2 - 10 keV range. This source is part of a sample of AGNs that have been the target of TeV observations by H.E.S.S. up to 2011 that show no significant excess in high-energy emission (H. E. S. S. Collaboration et al. 2014). There is no significant variability within the timescale of the observations for the default 500 s bins used.

5BZJ0613+7107 The redshift of this source is 0.267. Sixteen observations from 2000 to 2015 are contained in the catalogue. Eight observations show a weak X-ray source for which it is not possible to extract good-quality spectra. For the remaining observations, the most favoured fit is provided by a power law model with two absorption components, although in several observations a log parabolic model fits better. The flux ranges between $0.6 - 1.3 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2 - 10 keV range. There is no significant variability within the timescale of the observations for the default 500 s bins used.

5BZJ0721+7120 (also known as PKS 0716+714) has been extensively studied because of its intraday variability. Simultaneous radio, optical, UV, and X-ray observations yielded a short duty cycle of variability at all frequencies and a correlation between different wavelengths (Agudo et al. 2006). VLBI images show a compact, one-sided core jet (Bach et al. 2006). Of unknown redshift, five observations are found between 2001 and 2007 in our catalogue. In the 2001 and 2002 observations, this is a field source while in 2004 and 2007 it was the XMM–Newton target part of a target of opportunity (ToO) program to explore blazars in outburst. During 2004 and 2007 the source displayed high flux variability within the XMM–Newton observations, with rapid flares of the order of a few hours (Kushwaha & Paul 2010). During these observations the average flux was of the order of $1.0 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 0.2 - 10 keV range. In all observations the best fit is provided by a log parabolic model.

5BZJ0958+6533 This is a LSP BL Lac at $z = 0.367$ and famous for its intraday variability (Bach et al. 2006). It shows a one-sided jet structure that bends from milliarcsecond to arcsecond scales (Lico et al. 2016). There are three observations contained in our catalogue, one from 2005 and two from 2007. In all cases, the log parabolic model provides the best fit. The X-ray flux in the 0.2 - 10 keV range varies between 2.5 and $3.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The first observation in 2007 shows a
significant steady increase, a factor two, in flux over the course of the observation, more noticeable in the low 0.2-2.0 keV energy range, which results in a softening of the spectrum over the course of the observation.

**5BZBJ1136+1601** This BL Lac lies at $z = 0.574$. There are five observations contained in our catalogue taken between May and June 2014. In all cases, the best-fit model is a power law with two absorption components and photon index between 2.4 and 2.8. The X-ray flux in the 0.2 - 10 keV range varies between $2.2 - 2.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. There is no significant variability within the timescale of the observations for the default 500 s bins used.

**5BZBJ1210+3929** The redshift of this source is $z = 0.617$. We report nine observations in total from 2000 (2x), 2011 (3x), and 2012 (4x). All observations are best fitted by a power law with two absorption components. The photon index varies between 2.1 and 2.3 and the X-ray flux varies in the range $3.0 - 8.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.2 - 10 keV range. The source does not display significant source variability, being consistent with a constant source over the course of the observations.

**5BZBJ2258-3644** Of unknown redshift, two observations are present in the catalogue, from 2005 and 2015. In both cases the spectra are best fitted by a power law with two absorption components. The photon index of the 2005 observation is 2.9 and the flux $3.67 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.2 - 10 keV range; while in the 2015 the photon index is 3.33 and the flux $4.96 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the 0.2 - 10 keV range.