X-RAY SPECTRAL CURVATURE OF HIGH-FREQUENCY-PEAKED BL LAC OBJECTS: A PREDICTOR FOR THE TeV FLUX

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ABSTRACT

Most of the extragalactic sources detected at TeV energies are BL Lac objects. They belong to the subclass of high-frequency-peaked BL Lac objects (HBLs) exhibiting spectral energy distributions with a lower energy peak in the X-ray band; this is widely interpreted as synchrotron emission from relativistic electrons. The X-ray spectra are generally curved and well described in terms of a log-parabolic shape. In a previous investigation of TeV HBLs (TBLs) we found two correlations between their spectral parameters. (1) The synchrotron peak luminosity $L_p$ increases with its peak energy $E_p$, and (2) the curvature parameter $b$ decreases as $E_p$ increases. The first is consistent with the synchrotron scenario, while the second is expected from statistical/stochastic acceleration mechanisms for the emitting electrons. Here, we present an extensive X-ray analysis of a sample of HBLs observed with XMM-Newton and Swift but undetected at TeV energies (UBLs), to compare their spectral behavior with that of TBLs. Investigating the distributions of their spectral parameters and comparing the TBL X-ray spectra with that of UBLs, we develop a criterion to select the best HBL candidates for future TeV observations.

Key words: acceleration of particles – BL Lacertae objects: general – galaxies: active – radiation mechanisms: non-thermal – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The great majority (\textgreater 80\%) of the extragalactic sources detected up to 2011 April in $\gamma$-rays at TeV energies are BL Lac objects. These are a class of active galactic nuclei (AGNs) characterized by strong and highly variable non-thermal radiations from radio frequencies to TeV energies. Their observational properties include weak or absent emission lines, two-hump-shaped spectral energy distributions (SEDs, i.e., log $\nu F_\nu$ versus log $\nu$), high radio and optical polarization, and superluminal motions. These are interpreted as a result of radiation from a relativistic jet closely aligned to the line of sight (Blandford & Rees 1978).

BL Lac objects come in two types: the high-frequency-peaked BL Lac objects (HBLs) in which the low-energy component of the SED peaks between the UV band and X-rays, and the low-frequency-peaked BL Lac objects (LBLs) when the SED peak falls in the IR–optical range (Padovani & Giommi 1995). It is widely agreed that this low-energy component is produced by synchrotron radiation of ultrarelativistic particles (i.e., electrons) accelerated in the jets, while the high-energy component is likely due to inverse Compton scattering of the synchrotron photons by the same electron population (synchrotron self-Compton, SSC; see, e.g., Marscher & Gear 1985; Inoue & Takahara 1996).

In the following, we distinguish the HBLs detected at TeV energies from those that are undetected; we refer to the former as TBLs and to the latter as UBLs.

A useful phenomenological description of the BL Lac X-ray spectra was introduced by Landau et al. (1986) in terms of a log-parabolic (LP) model (i.e., a parabolic shape in a double-log plot); subsequently, this model has been frequently adopted for the low energy bump, e.g., by Tanihata et al. (2004), Massaro et al. (2004), and other authors. Recently, the high-energy component at TeV energies has also been successfully modeled with the same spectral shape (Massaro et al. 2006; Aharonian et al. 2009; Aleksic et al. 2011; Acciari et al. 2011; Abdo et al. 2011). We note that such LP synchrotron spectra are emitted by LP particle energy distributions (PEDs), obtained via the Fokker–Planck equation from a mono-energetic electron injection subjected to systematic and stochastic accelerations (Kardashev 1962; Massaro et al. 2006; Stawarz & Petrosian 2008; Paggi et al. 2009).

The LP model has also been used to describe the SEDs of other classes of jet-dominated sources: plerions (Campana et al. 2009), high-frequency-peaked (HFPs) radio sources (Maselli & Massaro 2009), and, recently, solar flares (Grigis & Benz 2008) and gamma-ray bursts (GRBs; Massaro et al. 2010a; Massaro & Grindlay 2011).

Adopting the LP model, the X-ray SED of HBLs is described in terms of three parameters: (1) the peak energy, $E_p$, in $\nu F_\nu$ space; (2) the maximum height of the SED, $S_p$, evaluated at $E_p$ (or the corresponding peak luminosity $L_p \simeq 4\pi D_L^2 S_p$, with $D_L$ being the luminosity distance); and (3) the spectral curvature, $b$, around $E_p$ (Tramacere et al. 2007, 2011; Massaro et al. 2008a, hereafter M08).

Extensive investigations of the TBLs, based on all the X-ray observations available in the BeppoSAX, XMM-Newton, and Swift archives between 1997 and 2007, have shown that several TBLs trace two correlations in the ($E_p$, $L_p$, $b$) parameter space: (1) the peak luminosity $L_p$ increases with $E_p$, as expected in the synchrotron scenario and (2) the curvature parameter $b$ decreases as $E_p$ increases (M08) as expected in a stochastic acceleration scenario (e.g., Tramacere et al. 2007).

As a result, TBLs cover a well-constrained region in the $E_p$–$b$ plane (hereinafter the “acceleration plane”). The correlation between $b$ and $E_p$ is evident for the 16 TBLs in M08, while no clear trend in the $E_p$–$L_p$ plane has been found for the whole sample.

Many HBLs have been targeted at TeV energies by HESS, MAGIC, and VERITAS, but by no means have all of them been detected. It is striking that 19 out of 24 TBLs (through...
Table 1

| Sample | $z_{\text{max}}$ | Total TBLs | HBLs | UBLs |
|--------|------------------|------------|------|------|
| 1ES    | 0.940            | 55         | 18   | 46   |
| HST    | 0.940            | 94         | 19   | 57   |
| SHBL   | 0.702            | 122        | 9    | 122  |
| RGB    | 0.664            | 109        | 7    | 70   |

Notes. Column 2: total number of BL Lac objects in the sample. Column 3: highest redshift in the sample. Column 4: number of TBLs present in the sample. Column 5: number of HBLs in the sample. Column 6: number of UBLs selected.

2010 August 1) belong to the Einstein Slew Survey Sample of BL Lacertae objects (1ES; Elvis et al. 1992; Perlman et al. 1996), which includes only the brightest X-ray extragalactic sources at $\sim$1 keV. The remaining TBLs belong to three different samples, namely, (1) the ROSAT All-Sky Survey-Green Bank BL Lac catalog (RGB; Laurent-Muehleisen et al. 1999), (2) the sedentary survey of extreme high-energy-peaked BL Lac objects (SHBL; Giommi et al. 2005), and (3) the Hubble Space Telescope (HST) Survey of BL Lacertae objects (Scarpa et al. 1999; Urry et al. 2000) (see Table 1). Consequently, we selected all the UBLs in the above four samples to search for possible differences between these sources and the TBLs.

In this paper, we present the sample selection criteria, the data reduction, and the data analysis procedures adopted to perform our investigation. Finally, comparing the distribution of the X-ray spectral parameters, we define criteria to predict future TBLs on the basis of X-ray observations only. The theoretical aspects and the interpretation of the observational results will be presented in F. Massaro et al. (2011, in preparation).

We use cgs units unless stated otherwise and we assume a flat cosmology with $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.26$, and $\Omega_{\Lambda} = 0.74$ (Dunkley 2009).

2. SAMPLE SELECTION

We chose all the sources classified as BL Lac objects or BL Lac candidates in the ROMA BZCAT\(^3\) (Massaro et al. 2009, 2010b) that are present in the four samples in which TBLs are found (see Section 1), excluding the TBLs.

To compare the behavior of TBLs and UBLs, we selected a sample of UBLs upon adopting the following criteria.

1. We calculated the ratio $\Phi_{\text{XR}}$ between the X-ray flux $F_{\text{X}}$ (0.1–2.4 keV) and the radio flux $S_{1.4}$ (at 1.4 GHz), $\Phi_{\text{XR}}$ (i.e., $\Phi_{\text{XR}} = 10^{-3} F_{\text{X}}/(S_{1.4} \Delta \nu)$ erg cm$^{-2}$ s$^{-1}$ Jy$^{-1}$ with $\Delta \nu = 1$ GHz), using the values of $F_{\text{X}}$ and $S_{1.4}$ reported in the ROMA BZCAT (Massaro et al. 2009, 2010b). We select BL Lac objects with $\Phi_{\text{XR}} \geq 0.1$ which corresponds to HBLs, according to the criterion established by Maselli & Massaro (2009).

2. We restricted our sample to those sources with redshifts $z \leq 0.539$, the highest redshift for an extragalactic TeV source (i.e., 3C 279; see Albert et al. 2008). Using this cut in redshift, we assumed that any extragalactic source with $z \geq 0.539$ could not be detected at TeV energies, because of the absorption by the extragalactic background light (Dwek & Krennrich 2005).

3. We considered only UBLs with X-ray observations up to the end of 2010 October in the XMM-Newton or Swift archives, as performed for the TBLs by M08 that have an exposure longer than 150 s, in order to have a good chance of detection and a sufficient number of counts to perform the X-ray spectral analysis (see also M08).

There are 118 UBLs with known redshifts in the four samples considered. However, 71 UBLs are excluded by requiring $\Phi_{\text{XR}} \geq 0.1, z \leq 0.539$ and with X-ray observations with exposures longer than 150 s. The remaining 47 UBLs constitute the sample we analyze below.

These 47 UBLs have been detected by a total of 135 X-ray observations: 123 by Swift observations and 12 by XMM-Newton. Only 19 UBLs out of the total 47 selected targets have been detected by Fermi during the first year of operations (Abdo et al. 2010). Table 1 reports the highest redshift for the sample (Column 2), the number of BL Lac objects identified in the ROMA BZCAT (Column 3), the number of TBLs in the sample (Column 4), the number of HBLs present (Column 5), and the UBLs selected according to the criteria defined above (Column 6).

The basic data for all 47 selected UBLs are reported in Table 2: the ROMA BZCAT name (Column 1) and sample name (Column 2), the equatorial coordinates (J2000) (Columns 3 and 4), the redshift (Column 5 from Massaro et al. 2010b), the luminosity distance $D_L$ (Column 6), the value of the Galactic column density $N_{H,Gal}$ (Column 7; see Kalberla et al. 2005), the X-ray to radio flux ratio $\Phi_{\text{XR}}$ (Column 8), and the number of both the XMM-Newton and Swift observations (Columns 9 and 10, respectively). Finally, in Column (11) we show the TeV candidate class provided by our investigation discussed in Section 6.

3. DATA REDUCTION PROCEDURES

The reduction procedure for the XMM-Newton data follows that described in Tramacere et al. (2007); additional details on both the XMM-Newton and Swift data reduction procedures can be found in M08 and Massaro et al. (2008b). In the following subsections we report only the basic details.

3.1. XMM-Newton Observations

The sources were observed with XMM-Newton by means of all EPIC CCD cameras: the EPIC-PN (Struder et al. 2001) and EPIC-MOS (Turner et al. 2001).

Extractions of light curves, source, and background spectra were done with the XMM-Newton Science Analysis System v6.5.0. The Calibration Index File and the summary file of the Observation Data File were generated using Updated Calibration Files following the User’s Guide to the XMM-Newton Science Analysis System (issue 3.1; Loiseau 2004) and The XMM-Newton ABC Guide (version 2.01; Snowden et al. 2004). Event files were produced by the EMCHAIN pipeline.

Light curves for each data set were extracted, and all high-background intervals filtered out to exclude time intervals contaminated by solar flares. Then, by visual inspection, we selected good time intervals far from solar flare peaks that have no count rate variations on timescales shorter than 500 s. Photons are extracted from an annular region using different apertures to minimize pileup, which affects MOS data. The mean value of the external radius used for the annular region is 40″.

A slightly restricted energy range (0.5–10 keV) is used to minimize residual calibration uncertainties. To ensure the validity of Gaussian statistics, data have been grouped by
## Table 2

| BZCAT Name       | Other Name | R.A. (J2000) | Decl. (J2000) | z   | \(D_L\) (Mpc) | \(N_{\text{H,Gal}}\) (10^{20} cm\(^{-2}\)) | \(\Phi_{\text{XR}}\) | Swift | XMM   | Fermi | TeV Class |
|------------------|------------|--------------|--------------|-----|----------------|---------------------------------------------|----------------|-------|-------|-------|-----------|
| BZB J0013−1854   | IRXS J001356.6−18540 | 00 13 56.0 | −18 54 06.0 | 0.094 | 420.1 | 2.13 | 2.24 | 4 | ... | 3 |
| BZB J0123+3420   | IES 0120+340 | 01 23 08.5 | +34 20 47.0 | 0.272 | 1359.7 | 5.20 | 5.74 | 17 | ... | ... |
| BZB J0201+0034   | IES 0200+000 | 02 01 60.1 | +00 34 00.0 | 0.298 | 1511.2 | 2.23 | 2.71 | 1 | ... | ... |
| BZB J0362+4553   | IRXS J036245.5+45530 | 03 62 38.2 | +45 32 13.0 | 0.318 | 1629.9 | 6.27 | 5.76 | ... | 2 | y | 2 |
| BZB J0414+5144   | RGB J0414+517 | 04 14 17.9 | +51 44 52.0 | 0.049 | 212.0 | 14.4 | 0.16 | 3 | ... | ... |
| BZB J0751+1730   | IRXS J075117.3+17300 | 07 51 25.0 | +17 30 51.0 | 0.185 | 878.4 | 4.93 | 1.78 | 1 | ... | ... |
| BZB J1053+2921   | IES 105329.2+29215 | 10 53 56.0 | +29 21 31.0 | 0.161 | 752.9 | 3.44 | 0.28 | 1 | ... | ... |
| BZB J1207+1143   | IES 120711.3+11434 | 12 07 13.8 | +11 53 50.0 | 0.199 | 953.2 | 3.17 | 3.39 | 1 | y | ... |
| BZB J1237+6258   | RGB J1237+6258 | 12 37 38.9 | +62 58 41.0 | 0.297 | 1505.3 | 0.97 | 1.90 | 13 | 2 | ... | ... |
| BZB J1253−3931   | IRXS J125314.2−39320 | 12 53 41.2 | −39 51 59.0 | 0.179 | 846.8 | 7.66 | 1.47 | 1 | ... | ... |
| BZB J1712+3142   | IRXS J171231.4+31424 | 17 12 57.9 | +31 42 39.0 | 0.141 | 650.8 | 1.25 | 5.16 | 1 | ... | ... |
| BZB J1728+4320   | IES 172843.2+43204 | 17 28 13.5 | +43 20 47.0 | 0.237 | 1161.3 | 1.54 | 1.72 | 5 | y | ... |
| BZB J1854−0915   | IRXS J185409.5−09150 | 18 54 36.3 | −09 15 21.0 | 0.449 | 2453.2 | 3.62 | 1.74 | 1 | ... | ... |
| BZB J2017+1707   | IRXS J201717.0+17065 | 20 17 01.5 | +17 07 00.0 | 0.169 | 794.4 | 2.91 | 5.92 | 2 | ... | ... |
| BZB J2250+3824   | RGB J2250+3824 | 22 50 05.7 | +38 24 37.0 | 0.119 | 541.2 | 10.4 | 0.24 | 16 | 1 | y | 2 |
| BZB J2308−2219   | IRXS J230847.6−22195 | 23 08 46.8 | −22 19 49.0 | 0.137 | 630.7 | 1.86 | 7.12 | 1 | ... | ... |
| BZB J2332+3436   | RGB J2332+3436 | 23 32 43.9 | +34 36 14.0 | 0.098 | 439.3 | 6.83 | 0.11 | 2 | ... | ... |
| BZB J2343+3439   | IRXS J234332.5+34395 | 23 43 33.5 | +34 39 48.9 | 0.366 | 1922.6 | 6.75 | 1.60 | 2 | ... | ... |

Notes. Column 1 indicates ROMA BZCAT source names. Column 2 indicates the name in the selected sample. Columns 3 and 4 indicate the right ascension and declination, respectively. Column 4 gives the redshift (from ROMA BZCAT). Column 5 reports the luminosity distance. Column 6 indicates the Galactic column density along the line of sight (Kalberla et al. 2005). Column 8 indicates the X-ray to radio flux ratio \(\Phi_{\text{XR}}\) (see Section 2). Columns 9 and 10 report the number of X-ray observations per satellite. Column 11 indicates if the source has been detected in the Fermi-LAT first year catalog, while Column 12 indicates the TeV candidate class derived from our analysis (see Section 6).

3.2. Swift Observations

The X-Ray Telescope (XRT) data analysis was performed with the XRTDAS software (v. 2.1), developed at the ASI Science Data Center (ASDC), and included in the HEASoft package (v. 6.0.2). Event files were calibrated and cleaned with standard filtering criteria using the xrtpipeline task.

Events in the energy range 0.3—10 keV with grades 0—12 (photon counting mode, PC) and 0—2 (windowed timing mode, WT) are used in the analyses; we refer to Hill et al. (2004) for a description of readout modes and to Burrows et al. (2005) for a definition of XRT event grades. This slightly broader band than for XMM-Newton has no effect on the spectral fits (see M08).
For the WT mode data, events were selected for temporal and spectral analysis using a 40 pixel wide (1 pixel = 2′.36) rectangular region centered on the source, and aligned along the WT one-dimensional stream in sky coordinates. Background events were extracted from a nearby source-free rectangular region of 40 × 20 pixels.

For PC mode data, when the source count rate is above 0.45 counts s⁻¹, the data are significantly affected by pileup in the inner part of the point-spread function (Moretti et al. 2005). To remove the pile-up contamination, we extract only events contained in an annular region centered on the source (e.g., Perri et al. 2007). The inner radius of the region was determined by comparing the observed profiles with the analytical model derived by Moretti et al. (2005) and typically has a 4 or 5 pixels radius, while the outer radius is 20 pixels for each observation.

For Swift observations in which the source count rate was below the pileup limit, events are instead extracted using a 20 pixel radius circle. The background for PC mode is estimated from a nearby source-free circular region of 20 pixel radius.

As for XMM-Newton, source spectra are binned to ensure a minimum of 30 counts bin⁻¹ in order to ensure the validity of χ²-statistics.

4. X-RAY SPECTRAL ANALYSIS

We performed our spectral analysis primarily with the Sherpa model fitting application (Freeman et al. 2001) and we used the xspec software package, version 12.6.0 (Arnaud 1996) as a check of our results.

We describe the X-ray continuum with different spectral models: (1) an absorbed power law with column density either free or fixed at the Galactic value N_{H, Gal}, (2) an LP model, and (3) a power law with an exponential cutoff (PEC) adopting the new expression described below (see Equation (3)). In all models with fixed Galactic column density, we use N_{H, Gal} values from the LAB survey (Kalberla et al. 2005) reported in Table 2.

The LP model is expressed in the form

\[ F(E) = KE^{-\alpha - b \log(E)}, \]

and the equivalent SED representation used by Tramacere et al. (2007) and M08 is expressed as

\[ F(E) = S_p E^{b \log(E/E_p)}, \]

with S_p = E_p^2 F(E_p). Both these representations are in units of photons cm⁻² s⁻¹ keV⁻¹. In particular, on using Equation (2), the values of the parameters E_p (the SED energy peak), S_p (the SED peak height at E_p), and b (the curvature parameter) can be evaluated independently in the fitting procedure (Massaro et al. 2006; Tramacere et al. 2007).

We used the following expression to define the PEC model:

\[ F(E) = \frac{\Sigma_p}{\epsilon_p^{\alpha}} \left( \frac{E}{\epsilon_p} \right)^{-\alpha} \exp \left[ \left( 1 - \frac{E}{\epsilon_p} \right)^2 \right]. \]

With Equation (3), the three parameters \(\epsilon_p\) (the SED energy peak), \(\Sigma_p\) (the SED height at the peak energy), and the photon index, \(\alpha\), can be evaluated independently in the fitting procedure. We emphasize that the independent estimates of spectral parameters in both LP and PEC models performed by Equations (2) and (3) allow us to investigate possible correlations among those parameters without the introduction of functional biases.

The results of the LP fits are reported in the Appendix; the statistical uncertainties quoted refer to the 68% confidence level (one Gaussian standard deviation).

In some cases, a combination of poor statistics (due to short observational exposures or low count rate), restricted instrumental energy range, or the location of E_p outside the observational energy range make it difficult to evaluate the spectral curvature. In all these cases the single power-law model is an acceptable description of the X-ray spectra.

For 31 out of the remaining 107 (29%) of the complete sample of X-ray observations the spectral curvature is consistent with zero within 1σ. For 28 out of 135 observations the number of counts did not allow us to perform a good spectral analysis. In these 59 observations, we added together several low signal-to-noise observations for each source (see the Appendix) and found that the co-added spectra are significantly curved in all cases.

5. RESULTS

5.1. X-Ray Spectral Properties

We present below the results of our X-ray spectral analysis performed on the NBL sample and compare them with the known X-ray spectral behavior of TBLs (see M08).

We excluded the case of PKS 2155–204 from the TBL sample, because on several occasions this source has shown a high-energy component dominating over the low energy one (e.g., Aharonian et al. 2009; Abdo et al. 2011; Acciari et al. 2011), making PKS 2155–204 more similar to a flat spectrum radio quasar than to an HBL.

We also excluded Mrk 421, because it has at least 10 times the number of X-ray observations than any other TBL, and so could dominate the parameter distributions.

Finally, we also excluded from our analysis the giant flare of Mrk 501 in 1997 (Massaro et al. 2006) and that of 1H 1426+428 (M08), because we are interested in investigating the spectral behavior in long-term quiescent states, rather than in rare, giant, flaring episodes.

We then compared all the NBL and TBL observations to search for possible differences in their X-ray spectral behavior that could lead to a possible criterion to identify TBL candidates. Our results are summarized as follows.

1. Spectral models. We find that the absorbed power-law model gave unacceptable values of χ² (i.e., χ² > 1.5) in all cases with sufficient statistics, for which the spectral curvature b could be estimated, even when the intrinsic low energy absorption is left as a free parameter. This model is also inadequate to describe the high energy tail of the X-ray spectra above ∼ 4 keV (see Figure 1, left panel).

Such a lack of intrinsic absorption agrees with the X-ray spectral analyses of TBLs, that are featureless over a broad energy range (i.e., 0.1–10 keV; Giommi et al. 2005; Perri et al. 2007; Tramacere et al. 2007; M08). An absence of spectral features related to any absorbing material was confirmed by Blustin et al. (2004), based on the XMM-Newton Reflection Grating Spectrometer spectra.

On the other hand, both the LP and the PEC models provide acceptable χ² values for all the UBLs (see the Appendix and Figure 1, right panel), and neither model can
Figure 1. Example of the XMM-Newton spectrum of BZB J0208+3523 performed on 2001 February 14 (ObsID: 0084140101) is reported here to show the goodness of the fitting procedure with the LP model relative to the standard power law. Left: the systematic deviations on both sides of the residuals from a best-fit power law with fixed $N_{\text{H, Gal}}$ show the need of intrinsic curvature. Right: the deviations disappear on using the LP model with fixed $N_{\text{H, Gal}}$.

Figure 2. X-ray $E_p$ distribution of UBLs (red) and TBLs (black). The sample of TBLs considered here does not include Mrk 421 and PKS 2155−304 and giant flares of Mrk 501 and 1H 1426+421, as described in Section 5. The maximum separation $D_{\text{KS}}$, of the two cumulative distributions, corresponding to the variable of the K-S test, is also shown in the plot.

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

Figure 3. X-ray curvature $b$ distribution of UBLs (red) and TBLs (black). The sample of TBLs considered here does not include Mrk 421, PKS 2155−304, and the giant flares of Mrk 501 and 1H 1426+421, as described in Section 5. The maximum separation, $D_{\text{KS}}$, of the two cumulative distributions (i.e., the variable used for the K-S test) and the corresponding boundary value of the curvature $b_*$ are also shown in the plot.

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

We found the following trends among the spectral parameters.

2. Peak energy $E_p$. The $E_p$ distribution for the UBLs is consistent with that of TBLs, exhibiting a peak around a value $\sim 1.75$ keV (Figure 2, left panel). There is a hint of a difference above the $E_p = 2.5$ keV; a K-S test (Figure 2, right panel) shows that the two distributions do not differ at a confidence level of 99%.

In addition, if we identify X-ray flares of HBLs as states where both $E_p$ and $L_p$ increase above their average values, then the scarcity of high $E_p$ (i.e., higher than $\sim 5$ keV) values found in our analysis suggests that TBLs are more variable than UBLs, because in random observations UBLs always appear in their quiescent state.

3. Spectral curvature $b$. There is a systematic difference in $b$ values between TBLs and UBLs (Figure 3, left panel). It is clear that the curvature in the latter is systematically higher, indicating that the NBL X-ray spectra are narrower around $E_p$ than those of TBLs. Applying a K-S test, the two distributions are different at a confidence level of 99%, and the maximum separation of the two cumulative distributions of $b$ occurs at the boundary value $b_* = 0.55$ (Figure 3, right panel). This implies that, given the two $b$ distributions, there be favored over the other in terms of $\chi^2$ and residuals. We performed a Kolmogorov–Smirnoff (K-S) test of the two distributions of $\chi^2$ and found that they are similar at the 99% level of confidence.

However, it is noteworthy that the $E_p$ values derived using the PEC model have larger uncertainties than those derived with the LP model. This is because with the PEC model, $E_p$ is directly related to the exponential cutoff, which is determined by the high energy tail of the X-ray spectra, which is not well sampled.

On the other hand, the LP model provides a systematically better description than PEC function for the TBL X-ray spectra (M08). Thus, to compare the TBL and NBL X-ray spectral properties, we adopted the LP model description.

We found the following trends among the spectral parameters.

2. Peak energy $E_p$. The $E_p$ distribution for the UBLs is consistent with that of TBLs, exhibiting a peak around a value $\sim 1.75$ keV (Figure 2, left panel). There is a hint of a
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Figure 4. Unfolded X-ray SEDs for four HBLs: two UBLs (dashed lines), BZBJ 0123+3420 (blue open squares, 2009-08-28) and BZBJ 2131−0915 (magenta open squares, 2009-03-30), in comparison with two archival observations of the TBLs (solid lines): Mrk 501 (black filled circles, 2006-20-07) and 1H 1426+428 (red filled circles, 2006-03-07) (see M08 for more details). The TBL X-ray spectra are broader than the UBLs.

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

is a low probability (~12%) of finding to find a TBL with X-ray spectral curvature higher than the boundary value \( b_\ast \) (Figure 5, right panel). Thus, \( b_\ast \) permits us to distinguish between TBLs and UBLs based on the X-ray spectral behavior. The stronger curvature in UBLs is also seen in the acceptable \( \chi^2 \) values when the PEC model is adopted. This occurs because the PEC model mimics high values of the spectral curvature due to its exponential cutoff than a typical LP model with \( b \sim 0.5 \). In Figure 4 we report the unfolded X-ray SEDs for four HBLs: two UBLs (dashed lines) BZBJ 0123+3420 and BZBJ 2131−0915, in comparison with two archival observations of the TBLs (solid lines): Mrk 501 and 1H 1426+428 to show the difference in their spectral curvature.

4. Spectral parameter trends. There is no clear correlation for the UBLs in the acceleration plane (\( E_p \) versus \( b \)), while for TBLs \( E_p \) and \( b \) anti-correlate (M08). On the other hand, there is no significant trend between \( L_p \) and \( b \) in either the UBLs or the TBLs (M08). All correlation coefficients evaluated between spectral parameters are lower than 0.1 for both LP and PEC models.

5.2. Variability

The NBL X-ray fluxes derived from our archival Swift and XMM-Newton analysis (from 2004 December to 2010 October) are consistent within a factor of ~2 with those measured, in the same energy range (i.e., 0.1−2.4 keV), ROSAT observations from ~15 years earlier (from 1990 June to 1999 February), as listed in the ROMA BZCAT (Massaro et al. 2010b). The ROSAT fluxes and those derived from our spectral analysis are reported in the Appendix. Only 18% of the selected UBLs show a flux ratio \( \rho = (F_{0.1-2.4\text{keV}})/F_{\text{ROSAT}} \) higher than 2 (see Figure 5). This suggests that UBLs vary little on a 20 year timescale, unlike TBLs which can show variability by a factor of ~5−10 over 1 year timescale.

5.3. Fermi-LAT Properties

The majority, 80%, of TBLs known up to 2010 October (19 out of 24) have been also detected in the “GeV” Fermi-LAT energy range (30 MeV−100 GeV) (Abdo et al. 2010). We searched the Fermi catalog for detections of UBLs and we found that only ~20% (24 out of 118) were detected. However, for the selected sample of 47 sources investigated here ~40% (19 out of 47) were detected by the Fermi-LAT. Because the majority of TBLs have been detected by Fermi, this could appear to be a requirement for being a TeV source. However, spectral variability may make them undetectable if they lie close to the Fermi detection threshold.

We compared the properties of TBLs and UBLs detected by Fermi to see if there are differences in their \( \gamma \)-ray properties. The Fermi-LAT “GeV” luminosity \( L_\gamma \) versus redshift is shown in Figure 6(a). There is a marginal indication that for the Fermi detections the UBLs are less luminous than TBLs, in particular at low redshifts, in agreement with the fact that most (~50%) of them in our analysis have not been detected.

The range of values of the \( \gamma \)-ray spectral index \( a_\gamma \) is similar between the TBLs and the UBLs detected by the Fermi-LAT (Figure 6(b)), the variance of the two distributions are 0.06 and 0.07, respectively. Figure 6(b) shows the \( \gamma \)-ray photon index \( a_\gamma \).
versus the average X-ray photon index ($a_X$) from the LP model, weighted with the inverse of the variance. We conclude that the MeV–GeV $\gamma$-ray spectral behavior of the UBLs is similar to that of the TBLs, and the only differences appear to reside in the normalization of their $\gamma$-ray flux. However, these conclusions are valid for those UBLs which are bright enough in the LAT energy range to be detected by Fermi during one year. The non-detected HBL could have a different $\gamma$-ray spectral behavior that cannot be investigated with the present data set.

6. HBLs DETECTABLE AT TeV ENERGIES

From comparing the distribution of the X-ray spectral curvature and the GeV Fermi-LAT detections, we propose criteria to predict which UBLs are more likely to be detectable at TeV energies.

TeV energies lie beyond the inverse Compton peak of the HBL SEDs. Hence to be detectable they need both a high GeV flux level and a small GeV–TeV spectral curvature. In the SSC scenario, the X-ray spectral curvature, $b$, of HBLs, evaluated at the synchrotron SED peak, $E_p$, is a good predictor of the curvature of the inverse Compton peak at GeV–TeV energies, although they are not always identical (Massaro et al. 2006).

We can define three levels of confidence (i.e., TeV classes) in the prediction of TeV detectability (see Table 2, Column 12).

Class 1: the best candidates for the future TeV detections are provided by UBLs with a GeV Fermi-LAT detection and a curvature, $b$, lower than $b_*$ in all the X-ray observations (see Figure 3(b)). We found that four UBLs satisfy both conditions and so are the most likely new TeV detectable extragalactic sources: BZB J0326+0225, BZB J0442–0018, BZB J0744+7433, and BZB J1743+1953. Spectral variability could limit this prediction but UBLs appear to be less variable in the X-ray band than TBLs (see Section 5.2 and Figure 5).

Class 2: six more UBLs have some X-ray observations with $b < b_*$ and are also detected by Fermi-LAT and so are still TeV candidates: BZB J0208+3523, BZB J1136+6737, BZB J1417+2543, BZB J1442+1200, BZB J1728+5013, BZB J2250+3824. The variability of $b$ leads us to expect the discovery of other new TBLs when their X-ray spectrum has $b < b_*$.

Class 3: UBLs with $b \leq b_*$ in at least one X-ray observations and $F_X \geq 10^{-11}$ erg s$^{-1}$ cm$^{-2}$ in the 0.5–10 keV energy range, but no LAT detection, make up our third class. The lower GeV normalization makes these less likely TeV candidates. However, in the single zone SSC scenario (e.g., Paggi et al. 2009), the X-ray flux is similar to the detection threshold of 1 yr Fermi-LAT $\gamma$-ray flux (Atwood et al. 2009) and the curvature is as broad as that of TBLs, we suggest that such UBLs can be detected at TeV energies. Five more UBLs fit class 3: BZB J0013–1854, BZB J0123+3420, BZB J0214+5144, BZB J1010–3119, and BZB J1253–3931.

Our source selection was concluded at the beginning of 2010 August. Since then, of the 15 total candidates, the sources BZB J1442+1200 and BZB J2250+3824 from our class 2 and BZB J0013–1854 and BZB J1010–3119 from class 3 have been detected at TeV energies (see the TeV CAT\footnote{http://tevcat.uchicago.edu/} for new announced TeV sources).

7. SUMMARY

We have carried out an extensive X-ray spectral analysis of HBLs to compare the spectral behavior of those undetected at TeV energies (UBLs) with those already known as TeV emitters (TBLs). We analyzed all 135 X-ray observations of a sample of 47 UBLs present in the XMM-Newton and Swift archives up to 2010 August.

We found that the $E_p$ distributions of UBLs and TBLs are similar and symmetric around a value of a few keV for both subclasses. Instead the X-ray spectral curvature, $b$, of UBLs is systematically lower than in TBLs, implying that the NBL X-ray spectra are narrower.

In addition, in the first year Fermi catalog (Abdo et al. 2010), we found that the NBL and TBL MeV–GeV $\gamma$-ray spectral behavior is similar, yet only $\sim$40% of our selected UBLs have been detected in the Fermi-LAT energy range versus 80% of TBLs (Abdo et al. 2010).

On the basis of our analysis, we have developed criteria to predict likely TBLs. We present three lists with different levels of confidence for TeV detectability based on MeV–GeV flux level and keV spectral curvature, comprising a total of 15 TeV candidates. By 2010 December, four of our candidates had already been detected at TeV energies, lending support to our selection criteria.

A crucial check for our TeV candidate criteria will be provided by X-ray monitoring of candidates from the different TeV classes, with simultaneous GeV and TeV observations, to investigate the variability timescales of the spectral curvature.

A theoretical interpretation of the $E_p$ and $b$ distributions, to both UBLs and TBLs, in terms of systematic and stochastic acceleration mechanisms will be presented in a forthcoming paper (F. Massaro et al. 2011, in preparation).

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Facilities: XMM, Swift, Fermi

Note added in proof. The source BZBJ1743+1935 (i.e., 1ES 1741+196) indicated, on the basis of our investigation, as a TeV candidate of class I, has been recently discovered at TeV energies as predicted by our study (see http://tevcat.uchicago.edu for more details). This observation supports our selection criteria for TeV candidates in the HBL subclass.

APPENDIX

RESULTS OF THE X-RAY SPECTRAL ANALYSIS FOR THE UBLs

Tables 3 and 4 report the log of the selected X-ray observations and the values of the spectral parameters we have derived for UBLs in our sample.

In Swift, Table 3, the column “Frame” reports on the observation modality (PC for photon counting and WT for windowed
| ObsID   | Date       | Frame | Exps | a       | b     | $E_p$ | K     | $S_p$ | $F_X$ | $\chi^2_r$ |
|---------|------------|-------|------|---------|-------|-------|-------|-------|-------|-----------|
| 00038117001 | 2009 Jun 5 | pc    | 5041 | 1.94(0.08) | 0.69(0.28) | 1.10(0.14) | 12(1) | 18.8(1.1) | 0.40 | 1.34(16) |
| 00038333001 | 2008 Dec 10 | pc    | 5040 | 1.72(0.07) | 0.65(0.13) | 1.62(0.12) | 49(1) | 83.6(2.6) | 1.67 | 0.96(53) |
| 00038333002 | 2008 Dec 11 | pc    | 780  | ...       | ...     | ...   | ...   | ...   | ...   | ...       |
| 00038333003 | 2009 Sep 16 | pc    | 3376 | 1.65(0.09) | 0.43(0.15) | 2.58(0.45) | 47(2) | 89.2(3.4) | 1.99 | 0.99(40) |
| 00038350001 | 2005 Jun 29 | pc    | 7671 | 2.85(0.13) | ...     | ...   | ...   | 3.9(0.3) | 0.11 | 1.26(8)   |
| 00038350002 | 2006 Jul 19 | pc    | 1951 | ...       | ...     | ...   | ...   | ...   | ...   | ...       |
| 00038350003 | 2007 Jun 8 | pc    | 346  | ...       | ...     | ...   | ...   | ...   | ...   | ...       |
| 00038350004 | 2008 Jul 16 | pc    | 9969 | 2.92(0.11) | ...     | ...   | ...   | 3.7(0.2) | 0.10 | 1.07(11)  |
| 00038819001 | 2009 Jul 29 | pc    | 949  | 0.90(0.52) | 1.47(1.14) | 2.37(0.78) | 17(2) | 43.4(5.1) | 0.84 | 0.63(2)   |

Table 3
Swift Spectral Analysis Results with the LP Model of the UBLs

| BZB J0013−1854 |       |       |       |       |       |       |       |       |       |         |
| BZB J0123+3420 |       |       |       |       |       |       |       |       |       |         |
| BZB J0214+5144 |       |       |       |       |       |       |       |       |       |         |
| BZB J0227+0202 |       |       |       |       |       |       |       |       |       |         |
| BZB J0325−1646 |       |       |       |       |       |       |       |       |       |         |
| BZB J0326+0225 |       |       |       |       |       |       |       |       |       |         |
| BZB J0441+1504 |       |       |       |       |       |       |       |       |       |         |
| BZB J0442−0018 |       |       |       |       |       |       |       |       |       |         |
| BZB J0621−3411 |       |       |       |       |       |       |       |       |       |         |

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**Notes:**
- The table presents Swift Spectral Analysis Results for various ObsIDs with different parameters including a, b, $E_p$, K, $S_p$, $F_X$, and $\chi^2_r$.
- Each row corresponds to a different observation with ObsID, Date, Frame, Exps, a, b, $E_p$, K, $S_p$, $F_X$, and $\chi^2_r$ values.

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**References:**
- The Astrophysical Journal, 739:73 (12pp), 2011 October 1
- Massaro et al., Table 3

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**Symbols:**
- ObsID: Observation Identifier
- Date: Date of observation
- Frame: Frame number
- Exps: Number of exposures
- a, b, $E_p$, K, $S_p$, $F_X$, $\chi^2_r$: Various parameters related to the spectral analysis

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**Additional Information:**
- The table includes a wide range of observational data, including various parameters that are crucial for understanding the spectral analysis results of the UBLs.
| ObsID | Date       | Frame | Exps | $a$      | $b$      | $E_p$   | $K$     | $S_p$   | $F_X$   | $\chi^2$ |
|-------|------------|-------|------|----------|----------|---------|---------|---------|---------|------------|
| BZB J0751+1730 | 2007 May 30 | pc    | 3102 | 1.20(0.41) | 1.33(0.88) | 2.01(0.43) | 6(1)  | 13.6(1.5) | 0.27  | 0.09(4)    |
| 00036808001     |  |       |      |          |          |         |         |         |         |            |
| BZB J0753+2921  | 2008 Mar 6  | pc    | 4500 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00036809001     |  |       |      |          |          |         |         |         |         |            |
| BZB J0847+1133  | 2008 Feb 29 | pc    | 2022 | 1.80(0.07) | ...      | 33(2)   | ...     | 1.63    | 0.85(20) |
| 00037396001     |  |       |      |          |          |         |         |         |         |            |
| BZB J0915+5238  | 2009 Mar 7  | pc    | 7710 | 2.08(0.06) | 0.55(0.18) | 0.84(0.14) | 9.5(0.4) | 15.4(0.7) | 0.32  | 0.65(23)   |
| 00038165001     |  |       |      |          |          |         |         |         |         |            |
| BZB J0930+4950  | 2010 Oct 12 | pc    | 2869 | 1.67(0.06) | 0.89(0.15) | 1.53(0.11) | 32(1)  | 54.8(2.3) | 1.20  | 0.73(29)   |
| 00039154001     |  |       |      |          |          |         |         |         |         |            |
| BZB J0952+7502  | 2007 May 20 | pc    | 9759 | 1.80(0.07) | 0.44(0.16) | 1.71(0.30) | 7.3(0.3) | 12.3(0.6) | 0.31  | 0.89(23)   |
| 00036810001     |  |       |      |          |          |         |         |         |         |            |
| BZB J1010−3119  | 2007 May 17 | pc    | 1481 | 2.00(0.09) | 0.46(0.23) | 1.00(0.24) | 43(2)  | 68.9(3.4) | 1.41  | 0.85(18)   |
| 00030940002     |  |       |      |          |          |         |         |         |         |            |
| BZB J1030+4029  | 2010 Oct 12 | pc    | 5703 | 1.60(0.12) | ...      | ...     | ...     | 8.6(0.5) | ...     | 0.49  | 1.61(14)   |
| 00037547001     |  |       |      |          |          |         |         |         |         |            |
| BZB J1053+4929  | 2010 Jan 21 | pc    | 5243 | 2.21(0.11) | 1.01(0.46) | 0.79(0.12) | 64(0.5) | 10.5(0.8) | 0.18  | 1.67(8)    |
| 00031594001     |  |       |      |          |          |         |         |         |         |            |
| BZB J1111+3452  | 2009 Apr 18 | pc    | 4590 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00038451001     |  |       |      |          |          |         |         |         |         |            |
| BZB J1136+6737  | 2007 Nov 9  | pc    | 2870 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00038451002     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154−0010  | 2009 Nov 8  | pc    | 2870 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00038451003     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154−0010  | 2010 Nov 8  | pc    | 1209 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00042002001     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2006 Nov 12 | pc    | 3114 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00042002002     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2006 Feb 15 | pc    | 6501 | 2.10(0.06) | 0.44(0.22) | 0.77(0.16) | 12(1)  | 20.0(0.8) | 0.43  | 1.02(25)   |
| 00060010001     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2006 Nov 14 | pc    | 2677 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00060010002     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2007 Apr 18 | pc    | 748  | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00060010003     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2007 Dec 6  | pc    | 2934 | 1.64(0.17) | 1.26(0.43) | 1.39(0.15) | 9(1)   | 14.6(1.3) | 0.28  | 0.57(5)    |
| 00060010004     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2008 Mar 3  | pc    | 1845 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00060010005     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2009 Oct 27 | pc    | 910  | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00060010006     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2009 Oct 28 | pc    | 1124 | ...      | ...      | ...     | ...     | ...     | ...     | ...        |
| 00060010007     |  |       |      |          |          |         |         |         |         |            |
| BZB J1154+6737  | 2010 Dec 20 | pc    | 4651 | 1.46(0.11) | 0.41(0.21) | 4.68(2.68) | 20(1)  | 47.5(4.7) | 1.08  | 0.65(25)   |
| 00037538001     |  |       |      |          |          |         |         |         |         |            |
| ObsID     | Date       | Frame | Exps | $a$     | $b$    | $E_p$   | $K$    | $S_p$    | $F_X$  | $\chi^2$ |
|-----------|------------|-------|------|---------|--------|---------|--------|----------|--------|----------|
| BZB J1257+2412 | 2008 May 9 | pc    | 2200 | 1.89(0.10) | 0.55(0.28) | 1.25(0.22) | 17(1) | 28.3(1.9) | 0.66  | 0.98(11) |
| BZB J1341+3959 | 2008 Oct 15 | pc    | 5198 | 1.63(0.06) | 0.70(0.14) | 1.84(0.18) | 23(1) | 41.2(1.5) | 0.98  | 0.96(37) |
| BZB J2201 | 2009 Dec 21 | pc    | 5901 | 1.64(0.07) | 0.70(0.16) | 1.82(0.19) | 14(0.6) | 25.1(1.2) | 0.60  | 1.42(26) |
| Sum       | 2010 Oct 10 | pc    | 11100| 1.66(0.04) | 0.66(0.10) | 1.82(0.14) | 18.1(0.5) | 32.3(0.1) | 0.78  | 1.04(63) |
| Sum       | 2010 Oct 15 | pc    | 3947 | 1.55(0.09) | 0.66(0.21) | 2.20(0.38) | 13(1) | 25.7(1.5) | 0.63  | 1.03(17) |
| BZB J1417+2543 | 2005 Dec 20 | pc    | 8547 | 1.83(0.04) | 0.43(0.08) | 1.59(0.14) | 64(2) | 106.6(2.9) | 2.69  | 0.92(69) |
| BZB J1439+3932 | 2008 May 26 | pc    | 775  | 1.72(0.15) | 0.88(0.59) | 1.44(0.34) | 84(7) | 142.1(11.6) | 3.08  | 1.07(6)  |
| BZB J1534+3715 | 2008 May 10 | pc    | 1694 | 1.75(0.10) | 0.39(0.34) | 2.08(1.24) | 51(2) | 86.8(6.7) | 2.25  | 1.78(10) |
| BZB J1605+5421 | 2008 May 9  | pc    | 832  | 2.18 (0.27) | ... | ... | ... | 19(3) | 0.78 | 1.86(2)  |
| Sum       | 2008 May 10 | pc    | 2290 | 2.42(0.08) | 0.64(0.29) | 0.47(0.17) | 18(1) | 33.6(2.6) | 0.52  | 0.82(12) |
| BZB J1728+5013 | 2005 Feb 26 | pc    | 1110 | 2.15(0.18) | ... | ... | ... | 42(5) | 1.59  | 1.02(3)  |
| BZB J1743+1935 | 2008 Mar 7 | pc    | 1058 | 1.80(0.20) | 1.36(0.57) | 1.18(0.15) | 43(4) | 70.2(6.4) | 1.27  | 1.79(3)  |
| BZB J2131−0915 | 2009 Mar 30 | pc    | 7066 | 1.37(0.12) | 0.84(0.33) | 2.36(0.61) | 5.0(0.3) | 10.5(0.8) | 0.24  | 0.94(10) |
| BZB J2201−1707 | 2007 Dec 8 | pc    | 4538 | 1.52(0.17) | 0.92(0.42) | 1.82(0.32) | 7(1)  | 12.8(1.0) | 0.28  | 0.65(7)  |
| BZB J2250+3824 | 2008 May 26 | pc    | 2996 | 2.47(0.14) | ... | ... | ... | 15(1) | 0.42  | 1.27(8)  |
| BZB J2307−2538 | 2008 May 17 | pc    | 1654 | 2.97(0.82) | ... | ... | ... | 15(2) | ...     | 0.34  | 1.25(3)  |
| Sum       | 2008 May 20 | pc    | 3446 | 2.55(0.12) | ... | ... | ... | 17(1) | ...     | 0.38  | 1.11(11) |
| Sum       | 2008 May 21 | pc    | 9205 | 2.43(0.06) | 0.29(0.18) | 0.19(0.02) | 17(1) | 39.4(12.3) | 0.45  | 0.66(33) |
| Sum       | 2008 May 22 | pc    | 1741 | 2.01(0.11) | 1.19(0.26) | 0.99(0.11) | 52(2) | 84.1(3.9) | 1.24  | 0.72(18) |
| Sum       | 2008 May 23 | pc    | 4130 | 2.19(0.08) | 0.98(0.25) | 0.80(0.10) | 70(3) | 114.1(5.1) | 1.62  | 0.55(23) |
| Sum       | 2008 May 24 | pc    | 3135 | 2.38(0.07) | ... | ... | ... | 58(2) | ...     | 1.75  | 1.09(17) |
| Sum       | 2008 May 25 | pc    | 782  | ... | ... | ... | ... | ... | ...     | ...   | ...      |
| Sum       | 2008 May 26 | pc    | 143  | ... | ... | ... | ... | ... | ...     | ...   | ...      |
| Sum       | 2008 May 27 | pc    | 9932 | 2.17(0.03) | 0.81(0.08) | 0.78(0.05) | 62(1) | 100.8(1.9) | 1.52  | 1.16(11) |
| Sum       | 2008 May 28 | pc    | 1429 | 2.07(0.13) | 0.87(0.46) | 0.91(0.20) | 49(3) | 78.0(4.8) | 1.24  | 1.20(12) |
| Sum       | 2008 May 29 | pc    | 3655 | 2.05(0.07) | 0.52(0.19) | 0.90(0.17) | 49(2) | 79.1(2.9) | 1.47  | 1.02(33) |
### Table 3
(Continued)

| ObsID         | Date       | Frame | Exps | $a$  | $b$  | $E_p$  | $K$  | $S_p$  | $F_x$ | $\chi^2$ |
|---------------|------------|-------|------|------|------|--------|------|--------|-------|---------|
| Sum           | ...        | pc    | 5084 | 2.07(0.06) | 0.63(0.14) | 0.88(0.11) | 49(1) | 79(2.4) | 1.38 | 1.06(47) |
| 00039211012   | 2010 Oct 12| pc    | 4933 | 2.04(0.09) | 0.66(0.21) | 0.93(0.16) | 62(3) | 100(4.2) | 1.76 | 1.22(25) |
| 00039211013   | 2010 Oct 12| pc    | 4382 | 1.80(0.09) | 0.79(0.20) | 1.33(0.12) | 69(3) | 114(4.9) | 2.18 | 0.68(26) |
| Sum           | ...        | pc    | 9536 | 1.91(0.06) | 0.78(0.13) | 1.14(0.08) | 64(2) | 103(3.0) | 1.87 | 0.96(55) |
| 00039211014   | 2010 Oct 14| pc    | 4676 | 1.91(0.09) | 0.87(0.25) | 1.12(0.11) | 63(3) | 100(4.3) | 1.76 | 1.26(27) |
| 00039211015   | 2010 Oct 15| pc    | 5316 | 2.02(0.05) | 1.01(0.14) | 0.97(0.06) | 52(1) | 82(2.4)  | 1.29 | 1.11(53) |
| 00039211016   | 2010 Oct 16| pc    | 3304 | 2.02(0.07) | 0.84(0.19) | 0.97(0.10) | 56(2) | 89(3.4)  | 1.48 | 0.95(31) |
| Sum           | ...        | pc    | 13300| 1.91(0.05) | 1.22(0.13) | 1.09(0.05) | 57(1) | 91(6.2)  | 1.41 | 0.93(64) |

**Notes.**

Column 7: $E_p$ is in keV.

Column 8: $K$ is in $10^{-4}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$.

Column 9: $S_p$ is in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

Column 10: $F_x$ denoting the 0.5–10 keV flux measured in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

### Table 4
**XMM-Newton** Spectral Analysis Results with the LP Model of the UBLs

| ObsID         | Date       | Frame | Exps | $a$  | $b$  | $E_p$  | $K$  | $S_p$  | $F_x$ | $\chi^2$ |
|---------------|------------|-------|------|------|------|--------|------|--------|-------|---------|
| BZB J0208+3523| 2001 Feb 14| M1-FW(Me) | 38070| 2.09(0.03) | 0.61(0.07) | 0.85(0.06) | 8.1(0.1) | 13.0(0.2) | 0.24 | 0.92(134) |
| 0084140101    | 2002 Feb 4  | M1-FW(Me) | 11680| 1.95(0.05) | 0.41(0.11) | 1.16(0.14) | 8.7(0.2) | 13.9(0.3) | 0.31 | 1.13(69)  |
| BZB J0326+0225| 2002 Feb 5  | M1-PW(Me) | 4563 | 2.36(0.07) | 0.32(0.16) | 0.27(0.21) | 18.4(0.4) | 36.6(7.3) | 0.50 | 0.68(47)  |
| 0094382501    | 2002 May 30 | pc    | 2381 | 1.60(0.13) | 1.34(0.30) | 1.40(0.10) | 24(1) | 41.7(2.5) | 0.73 | 1.17(14)  |
| BZB J0441+1504| 2003 Sep 5  | M1-PW(Me) | 7438 | 2.18(0.17) | ... | ... | 3.3(0.1) | ... | 0.11 | 1.57(15)  |
| 0203160101    | 2004 Apr 13 | M1-PW(Me) | 10620| 2.17(0.03) | 0.16(0.06) | 0.28(0.18) | 25.6(0.3) | 45.8(3.6) | 0.94 | 1.01(135) |
| BZB J0744+7433| 2004 Apr 12 | M1-PW(Me) | 19580| 2.19(0.03) | 0.18(0.06) | 0.30(0.15) | 23.4(0.3) | 42.0(2.8) | 0.84 | 1.00(141) |
| BZB J1231+6414| 2005 May 21 | M1-FW(Me) | 16220| 2.15(0.04) | 0.25(0.08) | 0.50(0.18) | 9.4(0.1) | 15.9(0.7) | 0.34 | 1.05(105) |
| BZB J1237+6258| 2009 Jul 9  | M2-FF(Th) | 9847 | 1.83(0.09) | 0.60(0.19) | 1.40(0.14) | 5.4(0.2) | 9.0(0.3)  | 0.21 | 0.85(41)  |
| 0604830201    | 2009 Dec 12 | M2-SW(Md) | 5788 | 2.00(0.04) | ... | ... | 20.9(0.4) | ... | 0.98 | 1.06(95)  |
| BZB J1510+333 | 2009 Jan 2  | M2-FF(Th) | 9844 | 1.64(0.02) | 0.45(0.11) | 2.53(0.35) | 7.8(0.2) | 14.9(0.4) | 0.38 | 1.14(64)  |
| BZB J1626+3513| 2007 Aug 17 | M2-FF(Md) | 7696 | 2.50(0.15) | ... | ... | 3.4(0.1) | ... | 0.10 | 0.65(12)  |
| 0505010501    | 2007 Aug 19 | M2-FF(Md) | 15300| 2.50(0.09) | ... | ... | 3.5(0.1) | ... | 0.11 | 0.93(28)  |

**Notes.**

Column 7: $E_p$ is in keV.

Column 8: $K$ is in $10^{-4}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$.

Column 9: $S_p$ is in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

Column 10: $F_x$ denoting the 0.5–10 keV flux measured in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

Timed, see also Section 3.2 for details), and “Exps” means the exposure time in seconds.

In XMM-Newton, Table 4, “Frame” indicates the EPIC camera used (M1=MOS1 and M2=MOS2), the modes (PW=partial window and FW=full window), and the filter (Th=thin, Md=medium, Tk=thick) used for each pointing (see Section 3.1 for details), and the exposure is reported in seconds in the column “Exps.”
Values of $E_p$ are reported in keV, the normalization $K$ in units of $10^{-4}$ photons cm$^{-2}$ s$^{-1}$ keV$^{-1}$, and $S_p$ in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ with $F_p$ denoting the 0.5–10 keV flux measured in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$.

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 710, 1271
Abdo, A. A., et al. 2011, ApJ, submitted (arXiv:1106.1348)
Acciari, V. A., Aliu, E., Arlen, T., et al. 2011, A&A, submitted (arXiv:1106.1210)
Aharonian, F., Akhperjanian, A. G., Anton, G., et al. 2009, A&A, 502, 749
Albert, J., Aliu, E., Anderhub, H., et al. 2008, Science, 320, 1752
Aleksic, J., Alvarez, E. A., Antonelli, L. A., et al. 2011, A&A, submitted (arXiv:1106.1589)
Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V. ed. G. Jacoby & J. Barnes (San Francisco: CA: ASP), 17
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Blandford, R. D., & Rees, M. J. 1978, in Proc. Pittsburgh Conf. on BL Lac Objects (Pittsburgh: PA: Univ. Pittsburgh), 328
Blustin, A. J., Page, M. J., & Branduardi-Raymont, G. 2004, A&A, 417, 61
Burrows, D., Hill, J. E., Nousek, J. A., et al. 2005, Space Sci. Rev., 120, 165
Campana, R., Massaro, E., & Mineo, T. 2009, A&A, 499, 847
Dunkley, J. J. 2009, ApJS, 180, 306
Dwek, E., & Krennrich, F. 2005, ApJ, 618, 657
Elvis, M., Plummer, D., Schachter, J., & Fabianno, G. 1992, ApJS, 80, 257
Freeman, P., Doe, S., & Siemiginowska, A. 2001, Proc. SPIE, 4477, 76
Giommi, P., Piranomonte, S., Perri, M., & Padovani, P. 2005, A&A, 434, 385
Grigis, P. G., & Benz, A. O. 2008, ApJ, 683, 1180
Hill, J. E., Burrows, D. N., Nousek, J. A., et al. 2004, Proc. SPIE, 5165, 217
Inoue, S., & Takahara, F. 1996, ApJ, 463, 555
Kalberla, P. M. W., Burton, W. B., & Hartmann, D. 2005, A&A, 440, 775
Kardashev, N. S. 1962, SvA, 6, 317
Landau, R., Bolsh, B., Jones, T. J., et al. 1986, ApJ, 308, 78
Laurent-Muehleisen, S. A., Kollgaard, R. I., Feigelson, E. D., Brinkmann, W., & Siebert, J. 1999, ApJ, 525, 127
Loose, N. 2004, User’s Guide to the XMM-Newton Science Analysis System, Issue 8.0 (http://xmm.esa.int/external/xmm_user_support/documentation/sas_usg/USG/)
Marscher, A. P., & Gear, W. K. 1985, ApJ, 298, 114
Masselli, A., & Massaro, E. 2009, Astron. Nachr., 330, 295
Massaro, E., Giommi, P., Leto, C., et al. 2009, A&A, 495, 691
Massaro, F., Giommi, P., & Tosti, G. 2008b, A&A, 489, 1047
Massaro, F., & Grindlay, J. E. 2011, ApJ, 727, L1
Massaro, F., Grindlay, J. E., & Paggi, A. 2010b, ApJ, 714, L299
Massaro, E., Perri, M., Giommi, P., Nesci, R., & Verrecchia, F. 2004, A&A, 422, 103
Massaro, F., Tramacere, A., Cavaliere, A., Perri, M., & Giommi, P. 2008a, A&A, 478, 395 (M08)
Massaro, E., Tramacere, A., Perri, M., Giommi, P., & Tosti, G. 2006, A&A, 448, 861
Massaro, E., et al. 2010b, A&A, submitted (arXiv:1006.0922)
Moretti, A., Campana, S., Mineo, T., et al. 2005, Proc. SPIE, 5989, 360
Padovani, P., & Giommi, P. 1995, MNras, 277, 1477
Paggi, A., Massaro, F., Vittorini, V., et al. 2009, A&A, 504, 821
Perlmutter, E. S., Stocke, J. T., Schachter, J. F., et al. 1996, ApJS, 104, 251
Perri, M., Masselli, A., Giommi, P., et al. 2007, A&A, 462, 889
Scarpa, R., Urry, C. M., Falomo, R., et al. 1999, ApJ, 521, 134
Snowden, S., Valencic, L., Perry, B., et al. 2004, The XMM-Newton ABC Guide (version 2.01) (http://heasarc.nasa.gov/docs/xmm/abc/)
Stawarz, S., & Petrosian 2008, ApJ, 681, 1725
Struder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18
Tanahata, C., Kato, J., Takahashi, T., et al. 2004, ApJ, 601, 759
Tramacere, A., Giommi, P., Perri, M., et al. 2009, A&A, 501, 879
Tramacere, A., Massaro, F., & Cavaliere, A. 2007, A&A, 466, 521
Tramacere, A., Massaro, E., & Taylor, A. M. 2011, ApJ, in press
Turner, M. L. J., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, 127
Urry, C. M., Scarpa, R., O’Dowd, M., et al. 2000, ApJ, 532, 816