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The Presence of X-ray Spectral Curvature in HBLs at Different Redshifts

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High-energy peaked BL Lacertae objects (HBLs) mostly show X-ray spectral curvature that provides an effective tool to study the physical conditions and dominant nonstationary processes in HBL jets. Our spectral study confirms the suggestion of some authors that the electrons in the jets of TeV-detected BL Lacertae sources should undergo an effective stochastic acceleration at the shock front yielding a lower curvature compared to the TeV-undetected ones. We have revealed some increase of the curvature parameter with redshift. However, this can also be related to a relatively poor data sampling at larger distances and the further intensive observations of the corresponding sources are necessary.

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1. Introduction

BL Lacertae objects (BLLs) are active galactic nuclei (AGN) of elliptical galaxies, which with quasi-featureless spectra, high optical and radio polarization, compact radio-morphology, strong flux variability and broad continuum extending from radio to very high energy γ-rays. These properties are explained as a result from a relativistically boosted non-thermal emission emanated by the jet closely aligned to the line-of-sight [1]. Their spectral energy distribution (SED) shows the presence of two broad components in the Log ν - Log νF_ν representation. The lower-energy component is explained via the synchrotron radiation emitted by relativistic electrons in the jet, while an inverse Compton (IC) scattering of synchrotron photons by the same electron population is thought to be a source for the high-frequency bump [2].

High-energy peaked BLLs (HBLs) are defined as BLLs with the lower-energy peak situated in the UV/X-ray part of the spectrum [3]. Therefore, these AGNs are expected (a) to be bright in the X-ray band and, therefore, detectable at large distances; (b) to show stronger and faster X-ray flux variability compared to other bands.

Previous X-ray spectral studies of HBLs (e.g. [4] - [11]) have shown that 0.1-10 keV spectra are rather well fitted with the log-parabolic model

$$F(E) = K(E/E_1)^{-a-b\ log(E/E_1)} \quad \text{ph cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}, \tag{1.1}$$

(E - photon energy; K - normalization factor; E_1 - reference energy, generally fixed to 1 keV; a - photon index at 1 keV; b - curvature parameter) compared to the single powerlaw

$$F(E) = KE^{-\Gamma}, \tag{1.2}$$

(Γ - the photon index throughout the spectral band). That is, X-ray spectra of HBLs are curved.

Both types of the spectral distribution can be established by systematic acceleration (e.g., electrostatic or electrodynamic) plus some statistical mechanisms [12]. The possible candidates for the log-parabolic case:

- So-called energy-dependent acceleration probability process (EDAP) related to the first-order Fermi acceleration at the shock wave front moving through the jet. In this case, the emitting particles are confined by a magnetic field with a confinement efficiency decreasing for an increasing gyration radius, and the probability for a further particle acceleration is lower when its energy increases [5].

- Stochastic (e.g. second-order Fermi process developed in the turbulent areas near the shock front) accelerations (obtained via the Fokker-Planck kinetic equation from a mono-energetic electron injection subjected to systematic and stochastic accelerations [13].

The curvature parameter of the log-parabolic energy distribution is inversely proportional to the stochastic acceleration rate [8]. Therefore, synchrotron SED is expected to be relatively broader (b ~0.3) when the stochastic acceleration is more efficient, while we should observe a narrower SED (b ~0.7) in the opposite case [8].

Thus, the presence of X-ray spectral curvature provides an effective tool to investigate the physical conditions and dominant nonstationary processes in HBL jets. The study of spectral curvature in the sources with different redshifts can give an indication about the cosmologic evolution of jet physical properties.

2. Results

Our intensive study [10], [11] of the curvature parameter from the XRT spectra of TeV-emitters 1ES 1959+650 (z=0.048) and PKS 2155-304 (z=0.116) shows that its distribution has a maximum at b = 0.35 - 0.37, i.e. the source mainly exhibited broader synchrotron SEDs, expected when the stochastic mechanism is more efficient [1]. Furthermore, our detection of an anti-correlation between the *b* parameter and the unabsorbed 0.3-10 keV flux shows a trend of lower curvatures with higher fluxes (i.e. broader SEDs in flaring states) while the higher curvatures are observed mainly during the lower brightness states. This result also favours a stochastic acceleration of the electrons producing X-ray photons during the flares.

However, the latter correlation was the case for the nearest bright HBL Markarian 421 (z=0.031) during the *BeppoSAX* observations performed during 1997-1998 [5]. Our spectral analysis of *Swift*-XRT observations of 2013 January-May, covering the violent X-ray flaring activities of Mrk 421, show that the 92% of the spectra are curved with b = 0.04 - 0.38 and the distribution maximum at b = 0.22. The a and b parameters are not correlated, and no significant anti-correlation is found also between b and $F_{0.3-10\mathrm{keV}}$ - there can be a mix of different acceleration scenarios and "contamination"by cooling processes (A. Tramacere, private communication).

Table 1 presents the summary of preliminary results of the search of X-ray spectral curvature for other HBLs sampled within different radshift ranges. In Column 3, the abbreviation TBL stands for a TeV-detected BLL, and UBL - for the opposite case. Column 5 gives the percentage of the curved spectra with respect the spectra with d.o.f. $>$ 10. On the basis of these results, we draw some conclusions in the next section.

3. Conclusions and Summary

- HBLs show a spectral curvature at any redshift they are detected (z=0.031-0.7). However, some sources do not show a curvature from the observations performed do date (e.g., 1ES 0347-121, 1H 0414+009) or the 60 – 80 percent of the spectra are described better by the single powerlaw (1ES 2344+514, 1ES 1218+304, Mrk 180, PKS 0548-322, PKS 2005-489, RGB J0710+591, 1ES 0806+524, 1ES 1421+528). This is not simply related to the spectral "poorness". For example, the seven spectra of the brightest HBL source Mrk 421 from the 2013 flaring period are not curved and their degrees of freedom are 63 - 305.

- In average, HBLs show an increasing curvature with redshift but this result can be an artifact of a poor data sampling at larger z values. In that case, there are much fewer observations and lower fluxes yielding relatively poor spectra. It is almost impossible to detect spectral curvature for the spectra with d.o.f. $<$10 (that corresponds to t_{obs} $<$3 ks for the *Swift*-XRT count rate of about 0.3 cts s^{-1}). It is not a good idea to add short observations to obtain a richer spectrum - BLLs show large and fast spectral variability and a sum of the spectra of different curvature can lead to an unacceptable value of reduced Chi-square.

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[1] We have used HeAsoft versions 6.15 – 6.16 and *Swift*-XRT CALDB versions 20131223 - 20140120 to process the raw X-ray data.

Table 1: Results of the search of X-ray spectral curvature in HBLs.

Source (1)	z (2)	TBL/UBL (3)	*b* (4)	% (5)	Citation (6)
$z \leq 0.05$					
Mrk 501	0.034	TBL	0.08-0.42[a]	85	TW
RX J0214.2+5144	0.049	UBL	0.41-0.65	100	[8]
Mrk 180	0.046	TBL	0.17-0.74	39	This work
1ES 2344+514	0.046	TBL	0.17-0.74	39	This work
$0.05 < z \leq 0.1$					
1ES 1727+502	0.055	TBL	0.28-0.65	62	This work
1RXS J001356.6-18540	0.094	TBL	0.36 - 0.68	100	[8]
PKS 0548-322	0.069	TBL	0.08 - 0.52	47	This work, [7]
1ES 1741+196	0.080	TBL	0.35 - 0.47	67	[8]
PKS 2005-489	0.071	TBL	-0.23 - 0.70	35	This work, [7]
$0.1 < z \leq 0.15$					
H 1426+428	0.129	TBL	- 0.22 Ű 0.28	54	This work
1ES 0323+022	0.147	UBL	0.42 - 0.43	100	[8]
RGB J0710+591	0.125	TBL	0.17 - 0.23	21	This work
1ES 0806+524	0.138	TBL	0.28 - 0.33[b]	20	This work
1RXS J101015.9-31190	0.143	UBL	0.46 - 0.76	100	[8]
RGB J1053+494	0.140	UBL	1.01(0.46)	100	[8]
RX J1136.5+6737	0.136	TBL	0.38 - 0.96	100	This work, [8]
1ES 1255+244	0.141	UBL	0.55(0.28)	100	[8]
1RXS J151040.8+33351	0.114	UBL	0.45(0.11)	100	[8]
$0.15 < z \leq 0.2$					
1ES 1218+304	0.182	TBL	0.15 - 0.37	33	This work
1RXS J075124.3+17304	0.185	UBL	1.33(0.88)	100	[8]
RGB J0916+526	0.190	UBL	0.55(0.18)	100	[8]
1RXS J093037.1+49502	0.187	UBL	0.89(0.15)	100	[8]
1RXS J095225.8+75021	0.179	UBL	0.44 - 0.58	100	[8]
1ES 1101-232	0.186	TBL	0.14 - 0.78	71	This work, [7]
1RXS J114535.8-03394	0.167	UBL	1.02 - 1.26	100	[8]
BZB J1231+6414	0.163	UBL	0.25(0.08)	100	[8]
1RXS J125341.2-39320	0.179	UBL	0.41(0.21)	100	[8]
RGB J1341+399	0.172	UBL	0.50 - 0.70	86	[8]
1ES 1440+122	0.163	TBL	0.32 - 1.36	80	[8]
1RXS J220156.0-17065	0.169	UBL	0.40 - 0.92	67	[8]
H 2356-309	0.165	TBL	0.22 - 0.78	100	This work, [7]
$0.2 < z \leq 0.3$					
1ES 1011+496	0.212	TBL	0.18 - 0.39	56	This work
1ES 0120+340	0.272	UBL	0.25 - 0.35	11	This work
1ES 0158+003	0.298	UBL	0.69(0.28)	100	[8]
1RXS J105607.0+02521	0.236	UBL	0.59(0.15)	100	[8]
1RXS J123739.2+62584	0.297	UBL	0.44 - 1.02	66	[8]
1RXS J141756.8+25432	0.237	UBL	0.43 - 0.88	86	[8]
1RXS J160518.5+54210	0.212	UBL	0.84(0.33)	100	[8]
$0.3 < z \leq 0.4$					
1ES 0502+675	0.314	TBL	0.28 - 0.70	100	This work
1RXS J020837.5+35231	0.318	UBL	0.41 - 0.61	100	[8]
EXO 0556.4-3838	0.302	UBL	0.28 - 0.74	100	This work
1ES 0737+746	0.314	UBL	0.16 - 0.18	100	[8]
1RXS J143917.7+39324	0.341	UBL	0.64(0.29)	100	[8]
1RXS J234332.5+34395	0.366	UBL	0.82 - 1.34	100	[8]

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[a] From the prolonged flaring activity during 2014 April-October observed with Swift-XRT; no significant correlation between the a and b as well between b and F0.3-10 keV is found.

[b] marginal detection.

Table 1: - Continued.

Source	z	TBL/UBL	b	%	Citation
$0.4<z\leq0.6$					
PG 1553+113	0.4-0.58	TBL	0.17-0.39^a	72	This work
1RXS J022716.6+02015	0.456	UBL	0.49 - 0.70	100	[8]
1RXS J044229.8-00182	0.449	UBL	0.45(0.32)	100	[8]
1RXS J062150.0-34114	0.529	UBL	0.90(0.52)	100	[8]
1RXS J213135.5-09152	0.449	UBL	0.76(0.22)	100	[8]
z>0.6					
1H 1515+660	0.7	UBL	0.18-0.53	80	This work
1RXS J003334.6-192130	0.610	UBL	0 .47(0.15)	33	This work
1RXS J020413.6-333345	0.617	UBL	0.47(0.15)	25	This work
1RXS J083251.9+330011	0.672	UBL	0.37 - 0.87	25	This work
1RXS J113755.4-171034	0.601	UBL	0.58 - 1.06	60	This work
1ES 1421+582	0.638	UBL	0.37 - 0.59	40	This work
1ES 1533+535	0.89(?)	UBL	0.26 - 0.89	100	This work

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[a] From two flares observed during the Swift-XRT 2012 and 2014 campaigns, respectively.

- Our results are mainly in agreement with the prediction of [8] that the electrons in the TBL jets should undergo a more efficient stochastic acceleration than in the UBL jets – they mostly show lower curvature ($\equiv$ wider SEDs) to be established in this case.

- TeV emission can be expected from following UBLs: 1ES 0120+340, EXO 0556.4-3838, 1ES 0737+746 , BZB J1231+6414, 1H 1515+660 - due to the presence of a low curvature. The extragalacric background light restricts their TeV-detection but they are closer than the farthest TeV source S3 0218+35 (z=0.944). Although other UBLs show higher curvatures that makes them unsuitable candidates for a TeV-detection, intensive study of nearby HBLs show that they sometimes also show high curvatures (above the "dividing line"b=0.55, derived in [8]), and they show large spectral variability with b = 0.3-0.4 that can be also the case for UBLs, leading to smaller curvatures in some epochs. Nevertheless, there are a few observations of UBLs allowing to reveal spectral curvature and, in many cases, the b parameter is determined below the 3σ significance and its high values can be simply related to larger errors. Therefore, more observations are needful to draw more firm conclusions.

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DISCUSSION

JIM HOWARTH BEALL: Is it possible to distinguish among the radiations coming from accretion disc and jet, respectively?

BIDZINA KAPANADZE: There is a clear difference between the spectra corresponding to jet and accretion disc. In the latter case, we observe prominent emission lines while the spectra are featureless for the radiation emanated by a jet that is the case for X-ray spectra of BL Lacertae objects, in contrast to flat-spectrum radio quasars (FSRQs) and Seyfert galaxies.

WOLFGANG KUNDT: Present-day astrophysics is full of erroneous ’conclusions’, because it lacks (stabilizing) tests. Stochastic particle acceleration to high energies is one of them; it easily violates the law of non-decreasing entropy.

BIDZINA KAPANADZE: The electron acceleration to highest energies in BL Lac jets is not due to only stochastic acceleration. Namely, there should be a combination of systematic coherent acceleration, responsible for the energy peak position of the log-parabolic spectrum, and of stochastic acceleration, which accounts for the SED broadening around its peak related to the lower spectral curvature (see, e. g., [8]).