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A First Synoptic Blazar Study Comprising Thirteen Blazars Visible in $E > 100$ GeV Gamma-Rays

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Abstract: Since 2002, the number of detected blazars at $E_\gamma > 100$ GeV has more than doubled. I study all currently known BL Lac-type objects with published energy spectra. Their intrinsic energy spectra are reconstructed by removing extragalactic background light attenuation effects. The emission properties are then compared and correlated among each other, with X-ray data, and with the individual black hole masses. In addition, I consider temporal properties of the very-high energy γ-ray flux. Key findings concern the flux–black hole mass and variability scale–black hole mass connections and the correlation of the spectral slope and the luminosity. As a specific application, the study allows to constrain the still undetermined redshift of PG 1553+113.

Introduction and Approach

In order to assess both the acceleration mechanisms in blazars and extragalactic background light (EBL) absorption effects, not only individual object studies, but also the investigation of a large sample of very-high energy (VHE) γ-ray emitting blazars is desirable. Ideally it should encompass a wide range in redshift for EBL studies and also include groups of sources at comparable distances in order to study intrinsic properties of the individual sources without possible systematic uncertainties caused by the EBL de-absorption. The preconditions for such comparative blazar studies have much improved recently. To date, the VHE γ-ray blazar sample comprises 18 BL Lac objects (e.g. [1]), with $z = 0.030 \ldots 0.212$.[1] A sample of all blazars with reported energy spectra is studied by inferring the intrinsic emission properties of the individual objects and by probing correlations of their VHE γ-ray and X-ray emission properties with black hole (BH) mass ($M_\bullet$) estimates.

Black Hole Masses. We estimate $M_\bullet$ by evaluating the $M_\bullet$-σ relation [2], i.e. the tight correlation of the stellar velocity dispersion σ and $M_\bullet$ of nearby galaxies. This approach assumes that AGN host galaxies are similar to inactive galaxies as far as the $M_\bullet$-σ relation is concerned. We find that the currently VHE γ-ray emitting BL Lacs are flatly distributed in $M_\bullet = (10^8 - 10^{9.5})\mathrm{M}_\odot$. Note that although AGNs harbor BHs with $M_\bullet > 10^6\mathrm{M}_\odot$, up to now only BL Lacs with $M_\bullet > 10^8\mathrm{M}_\odot$ have been discovered in VHE γ-rays.

Intrinsic VHE γ-Ray Emission Parameters. The photon spectra measured in the VHE range suffer absorption by EBL [3]. Here, the intrinsic blazar spectra are reconstructed using the EBL "low" model given in [4]. For sources that have been found in different flux states, "low state" and "flare" spectra are considered. Data from Mkn 421 [5], Mkn 501 [6], 1ES 2344+514 [7], 1ES 1959+650 [8], PKS 2155-304 [9], 1H 1426+428 [10], PKS 2005-489 [11], 1ES 1218+304 [12], H 2356-309 & 1ES 1101-232 [13], PG 1553+113 [14], Mkn 180 [15], PKS 0548-322 [16], BL Lac [17], and 1ES 1011+496 [18] have been included. Throughout this study, the unknown-redshift object PG 1553+113 is assumed at several possible z values, but not included further unless explicitly stated otherwise. The extracted observables are the intrinsic luminosity at 500 GeV and the intrinsic photon index Γ in the region around 500 GeV. For both, no extrapolations

1. See http://www.mppmu.mpg.de/~rwagner/sources/ for an up-to-date list.

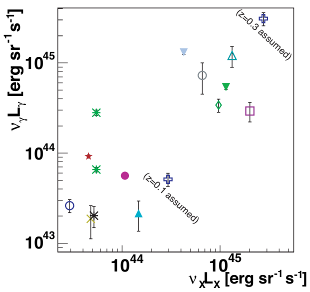

Figure 1: $\nu_\gamma L_\gamma$ vs. $\nu_{\rm X} L_{\rm X}$. The symbols are explained in Fig. 2. The PG 1553+113 points are for assumed $z = 0.1$ and $z = 0.3$.

beyond the spectral fits are required. The resulting intrinsic photon indices vary from $\Gamma = 1.5{-}3.3$. In most current acceleration models only $\Gamma > 1.5$ is allowed. This goes in line with indications that the EBL absorption effects are still smaller than modeled [13].

Correlation of X-ray and γ-Ray Luminosity

In SSC models, the X-ray and the VHE emission are closely connected, owing to their common origin. Fig. 1 shows $\nu_\gamma L_\gamma$ versus the X-ray luminosity at 1 keV ($\nu_{\rm X} L_{\rm X}$; from Costamante & Ghisellini 2002). A trend towards a correlation is visible, even though a strong correlation might not even be expected due to different magnetic fields in the individual objects. Note that high thermal contributions at 1 keV are unlikely and would imply a very high amount of gas and pressure.

Correlation between Photon Index and γ-Ray Luminosity

Fig. 2 relates the intrinsic photon indices Γ to $\nu_\gamma L_\gamma$. A correlation on the 3.3σ level is found, which, within SSC models, is compatible with a moving IC peak towards higher energies and an IC peak energy < 500 GeV. Sources with observed spectra at individual distinct flux states support this correlation. Mkn 501 and 1ES 2344+514 show a similar change in spectral slope and a luminosity

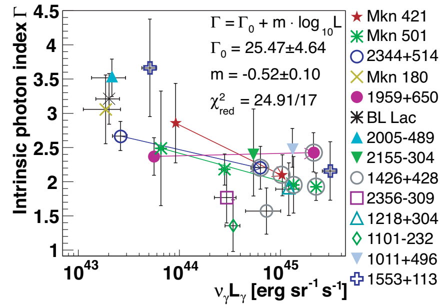

Figure 2: Photon index vs. $\nu_\gamma L_\gamma$. Additional flare states of sources are marked by gray circles. The PG 1553+113 points are not included in the fit. Arrows mark the four blazars with known low and high states.

increase of $\Delta(\nu_\gamma L_\gamma) \approx 20$. The luminosity increase of Mkn 421 is much lower with $\Delta(\nu_\gamma L_\gamma) \approx 10$.

Correlations of γ-Ray Emission with the BH Properties and z

The properties of blazar γ-ray emission are expected to be connected to BH properties, like $M_\bullet$ and its spin, since scaling laws govern BH physics, in particular length and time scales [19]. Currently, only $M_\bullet$ can be reliably estimated. The BH spin remains inaccessible by large; the accretion rate might be indirectly accessible through the (radio) jet power. A first study of the connection of source properties and $M_\bullet$ of the then-established five TeV blazars [20] did not find any correlations, except for an indication of a connection between the X-ray flare duty cycle and $M_\bullet$ (see below).

Fig. 3 shows the correlation of Γ and $\nu_\gamma L_\gamma$ with $M_\bullet$ and also tests for possible correlations with z. The latter are not expected from physics, but may identify selection effects in the data sample and/or an inaccurate EBL model. Only sources with hard intrinsic spectra are visible at large distances ($z > 0.1$), because soft spectra more easily fall below the current instrumental sensitivity limits. Another explanation for the prevalent hard spectra at large z is an overcorrection of the EBL attenuation effects. None of the nearby sources, for which no strong EBL modifications apply, show Γ much smaller than 2.0. Additionally, the detected

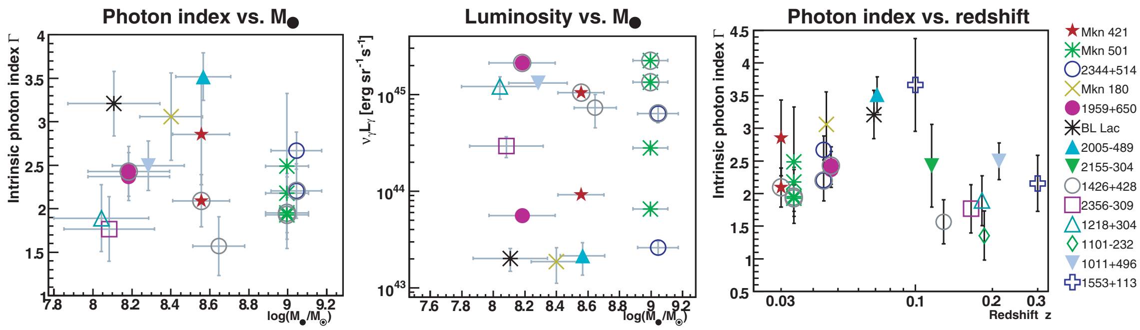

Figure 3: Correlations of Γ, $\nu_\gamma L_\gamma$ with $M_\bullet$, z. PG 1553+113 at assumed $z = 0.1$ and $z = 0.3$.

number of objects with soft spectra increased substantially since 2002.

While there is no obvious correlation between $M_\bullet$ and the VHE γ-ray luminosity, it might be that the current data populate only a certain area in the $M_\bullet$—Γ plane. Owing to the large uncertainties of the $M_\bullet$ determination and the still poor statistics, the future will have to show if such trends are real. Perhaps the VHE γ-ray emission is more sensitive to the BH spin, the accretion rate or, more importantly, to the acceleration environment rather than the BH mass. Also results on timing properties (see below) support such claims.

An Upper Redshift Limit for PG 1553+113

PG 1553+113 is a recently discovered TeV blazar [14] with unknown distance. With increasing redshift z, the intrinsic luminosity has to increase stronger than quadratic ($\nu_\gamma L_\gamma \geq 4\pi d^2 \cdot E^2 F$) due to EBL absorption as to sustain the measured VHE flux (Fig. 4). We assume here that PG 1553+113 is an "off the shelf" blazar, i.e. with no extraordinarily high L. This assumption is difficult to quantify, but when translating it into the limit that L is not more than 30 times higher than the highest luminosities observed, one obtains $z < 0.48$ (2σ limit). An extreme luminosity 1000-times higher yields a limit of $z < 0.68$. Among the extreme BL Lac objects we find $(\nu_\gamma L_\gamma)_{\max} < 10^{45.4}$ erg sr^{-1} s^{-1} for Mkn 501 in the flare state. These limits do not only depend on a good knowledge of the EBL attenuation over a wide range in redshift, but also on an assumed reasonable maximum VHE blazar luminosity that is strongly dependent on the Doppler factor δ. In any case, either a strikingly high luminosity or a very high δ is needed should PG 1553+113 be more distant than $z > 0.35$. Presumably such very extreme objects are so rare that a sufficiently large volume had to be probed to find one of them.

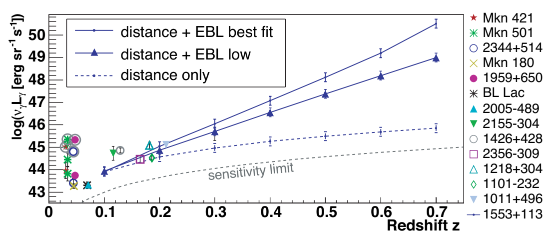

Figure 4: Luminosity evolution for PG 1553+113 at different assumed source distances.

X-ray Duty Cycle and VHE Variability Time Scale

Following a method described in [20] we determine the time fraction at which the 2-10 keV flux exceeds 50% of the average flux ("duty cycle", DC). In addition we require this deviation to be significant ($S > 3\sigma$). Note the outstanding DC of Mkn 421. Supporting the claim that variability is a defining property of BL Lacs, a flat distribution of the DC in $\nu_\gamma L_\gamma$ is found (Fig. 5). A previous study [20] including Mkn 421, Mkn 501, 1ES 2344+514, 1H 1426+428 and 1ES 1959+650 only had found indications for an anticorrelation of DC and $M_\bullet$, which in our enlarged sample is weakened mainly by the recently discovered sources H 2356-309, PKS 0548-322, and BL Lacertae.

Turning to the minimum VHE variability timescales τ, these do not scale with $M_\bullet$. This implies that flares originate from a much smaller region than the BH radius and (more importantly) that the BH properties do not influence the emission process too much, but the jet environment may be more important. Note that, in spite of the expected scaling behavior the TeV blazars hosting the more massive BH, Mkn 501 and Mkn 421, seem to exhibit the smallest τ. This, however, may be a selection effect caused (1) by their proximity, and (2) by instrumental sensitivity, as small τ measurements require strong sources. The latter also disables strong claims about τ-luminosity correlations yet, and all τ values are to be understood as upper limits.

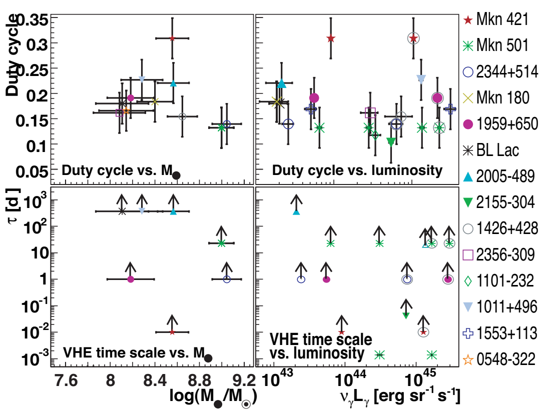

Figure 5: Correlations of X-ray duty cycle and VHE variability scales with $M_\bullet$ and $\nu_\gamma L_\gamma$.

Conclusions and Outlook

The observation of VHE blazars has started to become less biased: Not only blazars with hard spectra or in a flaring state are now detected, but a much higher dynamical range of VHE γ emission levels and states is probed, flare statistics studies (e.g. [21]) are within reach, and generic blazar properties start to become accessible. Thus the era of VHE blazar astronomy has been entered—astronomy being understood as the study of generic properties of a given class of objects.

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