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THE INTERMITTENT EXTREME BEHAVIOUR OF BL Lac 1ES 2344+514

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Abstract. The BL Lac object 1ES 2344+514 was one of the first sources to be included in the extreme high-peaked BL Lac (EHBL) family. EHBLs are characterised by a broadband spectral energy distribution featuring the synchrotron peak above $\sim 1\,\mathrm{keV}$. 1ES 2344+514 was detected in very-high-energy (VHE) gamma rays for the first time by the Whipple telescope in 1995. The extreme nature of 1ES 2344+514 in the X-ray band was observed in 1996, when Beppo-SAX detected a large 0.1–10 keV flux variability on timescales of a few hours, during another bright outburst in the X-ray band. This extreme behaviour of the source triggered several multiwavelength campaigns in the following years, during which the source appeared to be in a low state. In August 2016, FACT detected the source in a high state, triggering multiwavelength observations. The combination of MAGIC, FACT, and Fermi-LAT spectra provides an unprecedented characterisation of the inverse-Compton peak for this object during a flaring episode. We collected multiwavelength data, and modelled the broadband emission during this peculiar flaring episode using a leptonic and a hadronic model. The source was in an extreme synchrotron state. The peak frequency obtained from the leptonic model corresponds to a synchrotron peak ν_s at 18 keV. The shift of peak frequency with respect to previous observations is ~ 2 orders of magnitude. A harder than usual intrinsic VHE gamma-ray spectrum is observed, with $\Gamma = 2.04 \pm 0.12_{\mathrm{stat}} \pm 0.15_{\mathrm{sys}}$. The leptonic and hadronic models both describe successfully the data, but require a significantly different magnetisation of the emitting zone. Our conclusion is that 1ES 2344+514 belongs to a subcategory of EHBLs, which reveal to be extreme only in some circumstances.

1. INTRODUCTION

Blazars — active galactic nuclei (AGN) whose relativistic jets are pointed toward the observer — are commonly classified into two main groups: BL Lac objects (BL Lacs, after BL Lacertae) and flat spectrum radio quasars (FSRQ). This categorisation is based on the properties shown by their optical spectra (Urry & Padovani 1995). Blazars which emit in the very-high-energy (VHE, $E > 100\,\mathrm{GeV}$) γ-ray band belong in the majority of cases to the BL Lac family[1].

The broadband spectral energy distribution (SED) of blazars is characterised by a two-bumped structure (Ghisellini et al. 2017). While the first bump is universally attributed to synchrotron radiation by relativistic electrons, the bump situated at higher energies is often considered to be inverse-Compton (IC) scattering of the synchrotron photons by the same electron population. The simplest interpretation of the broadband SED of a blazar is given by a one-zone synchrotron self-Compton model (SSC). More complex scenarios include the presence of hadronic components (e.g., Cerruti et al. 2015) to describe the high-energy part of the broadband SED. BL Lac objects are divided into three subclasses, depending on the position of their synchrotron peak: low, intermediate, and high-frequency BL Lacs (Padovani & Giommi 1995; Böttcher 2007).

2. EXTREME BL Lacs

Some BL Lacs show a synchrotron peak ν_{s} at particularly high X-ray energies with $\nu_{\mathrm{s}} \geq 10^{17}\,\mathrm{Hz}$. Because of this extreme characteristic, they were proposed by Costamante et al. (2001) to be a new category of BL Lacs, namely extreme high-frequency BL Lacs (EHBL). EHBL can also have the IC bump peak shifted toward unusually high frequencies in the γ-ray band. In practice, this translates into particularly hard X-ray and VHE γ-ray spectra with a photon index $\Gamma \lesssim 2$.

[1] http://tevcat.uchicago.edu/ (Wackely & Horan 2008)

The archetypal EHBL, 1ES 0229+200 (Aharonian et al. 2007), exhibits these extreme properties in all observations performed so far, while other objects belong to the EHBL category only on some occasions (Ahnen et al. 2018; Foffano et al. 2019). During the observations reported here, we have found that BL Lac 1ES 2344+514 belongs to the latter group.

3. BL LAC 1ES 2344+514

1ES 2344+514 is a BL Lac located at redshift $z = 0.044$ (Perlman et al. 1996). It was discovered by the *Einstein* Slew Survey (Elvis et al. 1992). In 1996, 1ES 2344+514 showed a ν_s significantly above 10^{17} Hz during a flaring state, as reported by Giommi et al. (2000). 1ES 2344+514 was detected in the VHE γ-ray range for the first time in 1995 by the Whipple 10 m telescope, during an intense flare: on that occasion the flux detected by Whipple corresponded to $\sim 60\%$ of the Crab Nebula flux above 350 GeV (Catanese et al. 1998; Schroedter et al. 2005).

In the very bright flare of 1996, 1ES 2344+514 showed a remarkably variable behaviour in the X-ray band (Giommi et al. 2000, Costamante et al. 2001).The variability of the X-ray light curve was ~ 5 ks when the source was at its brightest state, and a large shift of ν_s was observed. At the same time the X-ray spectrum slope underwent very rapid changes. This was the occasion in which the source was marked as an EHBL for the first time.

After those events, several multiwavelength (MWL) campaigns monitored the source in search of simultaneous data which could have allowed a more precise interpretation of the emission scenario, modelling the broadband SED (Godambe et al. 2007; Albert et al. 2007; Acciari et al. 2011; Aleksic et al. 2013). During the course of those campaigns, though, the source was found in a lower state in the X-ray and VHE γ-ray band with respect to the previous observations (Catanese et al. 1998; Giommi et al. 2000). The broadband SEDs obtained in such a low activity state was sufficiently described by a one-zone SSC model.

Concerning the several VHE γ-ray observations by IACT (Imaging Atmospheric Cherenkov Telescopes), the source was found in variable flux states, but in general with integral fluxes lower than 10% of the Crab Nebula flux, excluding two short flares with 60% and 50% of the Crab Nebula flux level already mentioned (Catanese et al. 1998; Acciari et al. 2011). Recently, the temporal properties of 1ES 2344+514 in the VHE γ-ray band on short and long timescales have been investigated (Allen et al. 2017). No significant flaring activity has been observed since 2008.

4. RESULTS

In Acciari et al. (2020a), we reported on the observations of a VHE γ-ray flare of 1ES 2344+514 that happened in August 2016. The high activity in the VHE γ-ray range was first detected by FACT (First G-APD Cherenkov Telescope), which triggered the observations with the MAGIC (Major Atmospheric Gamma Imaging Cherenkov) telescopes. Many instruments, including *Fermi*-LAT (Large Area Telescope), *Swift*-XRT, *Swift*-UVOT (Ultraviolet/Optical Telescope), TCS (Telescope Carlos Sánchez), KAIT (Katzman Automatic Imaging Telescope, at Lick Observatory), KVA (Kungliga Vetenskapsakademien), Stella, LX-200, AZT-8, NOT (Nordic

Optical Telescope), IAC80, and OVRO (Owens Valley Radio Observatory) have observed this enhanced activity of 1ES 2344+514. We collected a dataset from simultaneous and quasi-simultaneous MWL observations which allowed us to study 1ES 2344+514 and for the first time provide the community with an unprecedented characterisation of the IC peak during a flaring state.

MAGIC observations started on MJD 57611 (11 August 2016; UT dates are used throughout this paper) and resulted in a detection with a significance of 13σ in less than one hour and a measured flux of 55% of the Crab Nebula flux above 300 GeV. This value of the flux is comparable to the historical maximum detected from this source in 1995 (Catanese et al. 1998). On the following night (MJD 57612, 12 August 2016) the signal was already fading and the measured flux was 16% of the Crab Nebula flux above 300 GeV. Using the data collected from instruments in the radio, optical, near-infrared, ultraviolet, X-ray, and HE band, we complemented the VHE γ-ray observations and built a broadband SED describing the flaring state with simultaneous data taken on MJD 57613 (13 August 2016). The SED has been modelled within two alternative scenarios: a leptonic SSC, and a proton-synchrotron model.

We have found the source in an extreme state, with a synchrotron peak frequency obtained from the leptonic model $\nu_{\rm s} \approx 4.3 \times 10^{18}$ Hz, corresponding to ~ 18 keV. The shift of $\nu_{\rm s}$ with respect to previous observations (Aleksic et al. 2013; Nilsson et al. 2018) is of about two orders of magnitude.

We also find a harder than usual VHE γ-ray spectrum ($\Gamma = 2.04 \pm 0.12_{\rm stat} \pm 0.15_{\rm sys}$ after extragalactic background light correction). The hardness of the spectrum does not vary between the first and the second night of observation, even though the flux on the second night was a factor of three lower.

The leptonic and hadronic models both successfully describe the data. On the other hand, they imply a significantly different magnetization of the emitting zone; in particular, the hadronic models require a much larger magnetic field, indicating that the emission zone has an equipartition parameter well above 1. The magnetic field energy densities in the case of the hadronic models are a factor of 10^2–10^4 higher than the energy density of the particles in the jet.

We conclude that the BL Lac object 1ES 2344+514 belongs to the subcategory of EHBL which appears extreme only in some circumstances (see Ahnen et al. 2018), and it does not exhibit the typical characteristic of persistent extreme SED as for instance the archetypal EHBL 1ES 0229+200 does (Aharonian et al. 2007).

5. FUTURE PLANS

This “intermittent” extremeness could be studied by acquiring more MWL data in the next few years. Time-dependent modelling to interpret the broadband SED could help to elucidate this peculiarity.

There is still more to discover about the EHBL family (Acciari et al. 2020b), and future MWL campaigns will help to unveil their nature and to move toward a classification of these interesting powerful AGN.

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