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# Long-term study of the intermittent extreme behaviour of 1ES 2344+514

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Extreme high-frequency-peaked BL Lac objects (EHBLs) are the most energetic persistent sources in the universe. They are characterized by a spectral energy distribution (SED) featuring a synchrotron peak energy above 1 keV. 1ES 2344+514 is a blazar known to behave as an EHBL intermittently. Until now, its EHBL nature was only reported during flares, but a coherent picture is missing as unbiased monitoring campaigns are lacking. This work presents the longest observing campaign from radio to very-high-energy (VHE) frequencies performed so far on 1ES2344+514. Using observations from between 2019-2021, we carry out a systematic investigation of the intermittent EHBL phases. The dataset also includes X-ray observations from *NuSTAR*, *XMM-Newton*, and *AstroSAT* together with MAGIC, providing an unprecedented determination of the two SED components. For the first time we report a clear EHBL behaviour during a low flux activity in 1ES 2344+514. It implies a significant hardening of the electron distribution inside the jet independent of flux. We also detect a bright X-ray state characterized by an unusually soft spectra, thus violating the harder-when-brighter relation typically found in blazars. The spectral study further reveals an excess in the ultraviolet data with respect to the extrapolation of the X-ray spectrum, suggesting at least two regions contributing to the synchrotron flux. Finally we investigate a gamma-ray flare not accompanied by an X-ray counterpart. This peculiar outburst is interpreted using a time-dependent model involving two emitting components.

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BL Lacertae (BL Lac) objects with a low-energy SED component peaking above 1 keV are dubbed as extreme high-frequency BL Lacs [EHBL; 1, 2]. EHBLs represent the most energetic persistent sources in the universe. Their study are particularly relevant in the context of particle acceleration in blazar jets given that their emission properties are challenging standard blazar models [3]. Furthermore, as discussed in [2], the EHBL population is non-homogeneous and exhibits various spectral and/or temporal properties. While some EHBLs are only extreme in the synchrotron domain, several of them also show an extreme behaviour at gamma-ray energies with a high-energy SED component peaking above 1 TeV. In addition, some blazars are EHBL-like temporarily (like e.g. 1ES 2344+514), while other seem to behave as EHBLs on a permanent basis.

1ES 2344+514 is a BL Lac object located at a redshift of $z = 0.044$ [4] and is one of the first extragalactic objects detected at very high energy (VHE; $E > 100$ GeV) [5]. The VHE flux typically lies between $\approx 4\%$ and $\approx 10\%$ of the Crab Nebula one [6–8]. The low-energy component of the spectral energy distribution (SED), attributed to synchrotron radiation, peaks in the X-ray band around 0.1 keV [9] during quiescent activity. It thus belongs to the sub-category of high-frequency BL Lac objects [HBL; 10]. Nonetheless, 1ES 2344+514 is known for strong X-ray spectral variability: during a flare the synchrotron peak energy increased by a factor of more than 30 on hour timescales and reached energies above 10 keV [11]. 1ES 2344+514 is thus characterised by an EHBL behaviour occurring on a temporary basis, which seems to happen mostly during high emission periods.

The intermittent EHBL nature of 1ES 2344+514 is poorly characterised due to the lack of multi-year broadband campaigns performed so far. The underlying physical mechanisms responsible for the EHBL states and how they correlate with the flux activity remain to be understood. To tackle this question, we organised a 3-year multi-wavelength monitoring campaign between 2019 and 2021. We coordinated observations from a large sample of instruments to cover the SED from the radio to the VHE band. At VHE, the observations were carried out by the MAGIC telescopes within a long-term monitoring program of the source. To accompany the MAGIC exposures, we further organised many pointings from the *Neil Gehrels Swift Observatory* (*Swift*) to obtain a simultaneous UV and X-ray characterisation. Additional sensitive X-ray observations were obtained thanks to multi-hour exposures by *XMM-Newton*, *NuSTAR* and *AstroSat* that happened simultaneously to MAGIC observations.

Between 2020 and 2021, the MAGIC measurements unveil on average a low VHE activity without significant flare. The yearly 2020 mean flux is at the level of 4% of the Crab Nebula flux above 300 GeV, while in 2021 it is about 2% of the Crab Nebula, which is among the lowest state reported for the source so far. At other wavebands, a generally low activity is also measured. Differently, 2019 is characterised by a VHE flare with a peak activity of $\approx 20\%$ of the Crab Nebula flux above 300 GeV. A hint of MeV-GeV flare is also visible in the *Fermi*-LAT data. We monitored the flare over several days using MAGIC, *Fermi*-LAT, *Swift* and optical telescope in order to obtain time-resolved SEDs on daily timescales. We find an absence of strong correlation of the 0.3-2 keV flux with the VHE band, while the 2-10 keV emission seems to well correlate with the VHE flux. At optical and radio bands, no variability is detected. We interpret the flare using a multi-zone time-dependent leptonic model in which the 2-10 keV & gamma-ray flare is induced by a compact region filled with an energetic electron distribution. The broadband SED is well reproduced by taking into account synchrotron and inverse-Compton cooling as well as adiabatic expansion of the emitting region.

The gathered data set allows us to systematically investigate the EHBL states, both in the X-ray and gamma-ray domains. We find that the X-ray spectra show a general indication for a "harder-when-brighter" trend, confirming that EHBL phases of the sources are more likely to occur during elevated flux periods. Nonetheless, the *Swift* X-ray Telescope (XRT) reveals several occurrences of a clear violation of the "harder-when-brighter" relation. Figure 1 exposes two *Swift*-XRT SEDs collected in 2019 during flares: one on August $6^{\text{th}}$ 2019 (blue points), and another one on October $5^{\text{th}}$ 2019 (violet markers). The grey data points are archival measurements retrieved from the SSDC database[1]. The *Swift*-XRT SED on August $6^{\text{th}}$ 2022, during which MAGIC observations unveil a simultaneous VHE flare, is characterised by a hard spectrum, with a best-fit power-law index of $\Gamma_{XRT} = 1.76 \pm 0.09$. This implies a synchrotron peak significantly above 1 keV, in line with an EHBL state. Regarding the *Swift*-XRT spectrum of October $5^{\text{th}}$ 2019, which is among the brightest for 1ES 2344+514 (see for comparison the archival data in grey markers), it is significantly softer, $\Gamma_{XRT} = 2.17 \pm 0.04$. In fact, it represents one of the softest spectra of the campaign, which thus contradicts the usual "harder-when-brighter" relation found in blazars. We note that during this period, MAGIC data does not show any significant increase of the VHE activity (around 8% of the Crab Nebula flux above 300 GeV). We also find periods with hard *Swift*-XRT spectra (synchrotron peak $>$ 1 keV) when the source is in low activity. This indicates drastic shifts of the synchrotron component to higher energies independently from the source activity. Consequently, changes in the electron acceleration efficiency likely exists with stable electron injection luminosity in the emitting zone.

In a forthcoming publication, we model the broadband SEDs collected during the simultaneous MAGIC, *XMM-Newton*, *NuSTAR*, *AstroSat* multi-hour exposures since they provide an unprecedented characterisation of the source. We find that they are best described using a two-component model, in which a low-energetic region possibly associated to the radio core significantly contributes to the observed synchrotron flux. The X-ray and gamma-ray emission is produced by a more compact and energetic component inside the jet. The two-zone configuration is motivated by an excess of the UV data compared to the extrapolation to lower energies of the X-ray spectrum.

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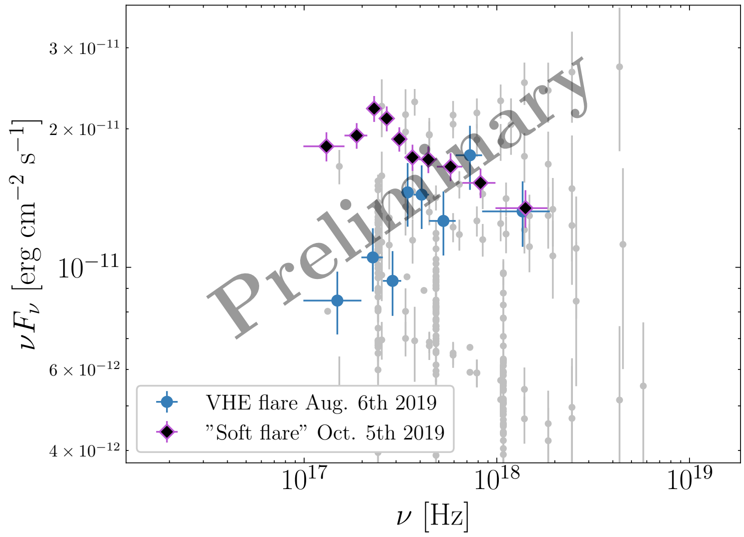


**Figure 1:** *Swift*-XRT SED during August 6th 2019 (blue markers) and October 5th 2019 (violet diamond markers). Archival data are plotted in grey and are taken from the SSDC database. While the SED on August 6th 2019 show a simultaneous bright VHE flare, the observations on Ocotber 5th 2019 are accompanied by a VHE flux close to the average state.

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