PROCEEDINGS OF SCIENCE

Exploring the Most Extreme Blazars: New Insights from MAGIC

L. Foffano,[a,*] C. Arcaro,[b] A. Arbet-Engels,[c] F. D'Ammando,[a] P. Da Vela,[a] J. Jormanainen,[e] D. Linder,[f] S. Menon,[a] E. Prandini,[b] S. Ventura[d] and E. Visentin,[g] for the MAGIC Collaboration

[a] *National Institute for Astrophysics (INAF), I-00136 Rome, Italy*
[b] *Università di Padova and INFN, I-35131 Padova, Italy*
[c] *Max-Planck-Institut für Physik, D-85748 Garching, Germany*
[d] *Università di Siena and INFN Pisa, I-53100 Siena, Italy*
[e] *Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, Department of Physics and Astronomy, University of Turku, FI-20014 Turku, Finland*
[f] *ETH Zürich, CH-8093 Zürich, Switzerland*
[g] *INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy*

E-mail: luca.foffano@inaf.it

Extremely high-peaked BL Lac objects (or extreme blazars) are unique extragalactic laboratories where particle acceleration processes are pushed at their physical limits. In these blazars, synchrotron emission peaking above keV energies is reprocessed to very-high-energy (VHE, energies > 100 GeV) gamma rays, often resulting in very hard TeV spectra. Over the past two decades, they have attracted a growing interest from the scientific community, both experimentally and theoretically, as crucial targets for understanding the diversity within the blazar class. On the experimental side, new sources have been detected and characterized, populating the extreme blazars class. Notably, VHE campaigns have revealed evidence of emerging spectral differences in this energy band, suggesting inhomogeneity within this class of sources. Recent studies have also unveiled intriguing differences in the temporal evolution of their spectral emission. On the theoretical side, these spectral differences are challenging the current standard emission and acceleration models for blazars, suggesting the need for more complex theoretical frameworks. In this contribution, we present the latest results from recent MAGIC Collaboration observing campaigns aimed to enlarge the extreme blazars population at VHE and understand the origin of their extreme properties. Furthermore, we will present the results of the most recent observations, discussing analogies and differences with well-known sources such as the archetypal 1ES 0229+200, as well as interpretations of their non-conventional spectral emission.

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1. Introduction

Among the large class of active galactic nuclei, blazars are characterized by a relativistic jet pointing directly towards to the observer, making them valuable sources to directly explore their particle acceleration mechanisms.

Blazars constitute an heterogeneous population of sources, subdivided in subclasses based on their radiation efficiency [e.g. 1]. BL Lac objects are blazars with lower environmental particle density, which implies a lower luminosity and higher particle acceleration efficiency. The most energetic sources of this class are called *extreme blazars* [e.g. 2], a short name indicating Extremely High-Peaked BL Lac objects (EHBLs). Their spectral energy distribution (SED) typically displays two emission components. Extreme blazars are defined on the basis of their synchrotron peak energy, which lies above 10^{17} Hz ($\sim$ 0.3 keV) in the X-ray band [3]. This low-energy emission is then reprocessed and produces a bump of radiation in the SED extending deeply into very high-energy (VHE, E>100 GeV) gamma-ray band, whose origin is attributed mainly to inverse Compton emission of the synchrotron photons [SSC emission, 4, 5] with possible additional contributions of further leptonic-hadronic components [e.g., 6].

These extreme energies - which are optimally investigated by the MAGIC telescopes - turn out to be key to understanding the physical processes behind their extreme properties and to test them as cosmological probes [e.g., 7]. In fact, at TeV energies, the extreme blazar population appears to be divided into heterogeneous classes of sources [8]. Some of them show extremely hard TeV spectra - named *hard-TeV* extreme blazars - while others show softer spectra. Some specific sources have experienced large flux variations, showing temporarily characteristics of extreme blazars during flaring episodes, for example in the case of 1ES 2344+512 [9, 10] and 1ES 1959+650 [11].

The interpretation of such exotic and various spectral properties is still challenging within the existing theoretical models, requiring extreme parameter values. The growth of their population represent a key to improve our understanding on the physical processes behind their extreme properties.

2. Extreme blazars at TeV gamma-ray energies

The low radiation efficiency of extreme blazars - combined with their enhanced particle acceleration efficiency and diverse possible spectral properties - makes these objects hard to be detected at TeV energies. To address the search for new TeV extreme blazars, systematic observations are carried out on the basis of a list of promising targets. Such candidates are selected among catalogs of blazars based on a complex set of observational criteria - such as hardness of the spectrum in X-rays and gamma rays, estimated redshift, and multi-wavelength correlations supporting their classification as extreme blazars - which make these sources likely detectable at TeV energies with the current generation of Cherenkov telescopes. As a result, the population of known TeV extreme blazars is steadily growing, driven by the ongoing discovery of new sources in this energy range.

3. A new catalog of MAGIC extreme blazars

The MAGIC telescopes are a system of two 17-m diameter imaging atmospheric Cherenkov telescopes (IACTs) located at an altitude of 2200 m above sea level on the island of La Palma, in Spain.

They sensitivity is optimized for gamma-ray photons with energies ranging from about 20 GeV to 100 TeV [12, 13].

In this contribution, we present the results of the long-standing observing program led by the MAGIC Collaboration dedicated to the search for new TeV extreme blazars, aimed at extending their population and characterizing their emission behavior. This program has already proven successful, providing to the community several new EHBL detections at TeV energies.

This study allows us to build a new catalog of 11 sources, based on MAGIC observations carried out between 2017 and 2025, investigating their flux variability and spectral properties. Among them, we provide new long-term monitoring data of 3 known extreme blazars, extending the findings of our previous publication [14]. In addition, the catalog includes – for the first time – data on 8 further sources, providing new TeV detections. Complementary multi-wavelength observations in the optical-UV and X-ray bands were carried out with dense temporal and spectral coverage. This rich dataset allows us to investigate and test various theoretical scenarios describing the underlying emission processes. The complete set of results and the comparison among this various set of sources allow us to discuss interesting physical processes of the category of extreme blazars.

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