PROCEEDINGS OF SCIENCE

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

A. Arbet-Engels,[a,*] H. A. Mondal,[b] S. Fukami,[c] F. D'Ammando,[d] D. Dorner,[f] R. Chatterjee,[e] P. Majumdar,[b] M. Manganaro,[g] T. Hovatta,[j,m] for the MAGIC collaboration, S. Das,[e] C. M. Raiteri,[i] M. Villata,[i] M. Perri,[h,n] F. Verrechia,[h,n] C. Leto,[h,l] A. Filippenko[o,p] and W. Zheng[o]

[a] *Max-Planck-Institut für Physik, D-80805 München, Germany*
[b] *Saha Inst. of Nuclear Physics, A CI of Homi Bhabha National Inst., Kolkata 700064, West Bengal, India*
[c] *ETH Zürich, CH-8093 Zürich, Switzerland*
[d] *INAF - Istituto di Radioastronomia, Via Gobetti 101, I-40129 Bologna, Italy*
[e] *School of Astrophysics, Presidency University, 86/1 College Street, Kolkata 700073, India*
[f] *Universität Würzburg, D-97074 Würzburg, Germany*
[g] *University of Rijeka, Faculty of Physics, 51000 Rijeka, Croatia*
[h] *Space Science Data Center (SSDC) - ASI, via del Politecnico, s.n.c., I-00133, Roma, Italy*
[i] *INAF—Osservatorio Astrofisico di Torino, I-10025 Pino Torinese, Italy*
[j] *Finnish Centre for Astronomy with ESO (FINCA), University of Turku, FI-20014, Turku, Finland*
[m] *Aalto University Metsähovi Radio Observatory, Metsähovintie 114, 02540 Kylmälä, Finland*
[l] *Italian Space Agency, ASI, via del Politecnico snc, 00133 Roma, Italy*
[n] *INAF - Osservatorio Astronomico di Roma, via di Frascati 33,I-00040 Monteporzio, Italy*
[o] *Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA*
[p] *Miller Senior Fellow, Miller Institute for Basic Research in Science, University of California, Berkeley, CA 94720, USA*

E-mail: aarbet@mpp.mpg.de

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 during 2019-2021, we carry out a systematic investigation of the intermittent EHBL phases. Together with MAGIC, the dataset also includes X-ray observations from *NuSTAR*, *XMM-Newton*, and *AstroSAT*, 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 SED 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.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)788

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. Additional optical data were collected in the R-band using the GASP-WEBT, Tuorla and KAIT monitoring programs. At lower frequencies, radio observations were performed by the OVRO telescope.

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.

References

[1] Costamante L., Ghisellini G., Giommi P., Tagliaferri G., Celotti A., Chiaberge M., Fossati G., et al., 2001, A&A, 371, 512. doi:10.1051/0004-6361:20010412

[2] Biteau J., Prandini E., Costamante L., Lemoine M., Padovani P., Pueschel E., Resconi E., et al., 2020, NatAs, 4, 124. doi:10.1038/s41550-019-0988-4

[3] Kaufmann S., Wagner S. J., Tibolla O., Hauser M., 2011, A&A, 534, A130. doi:10.1051/0004-6361/201117215

[1] https://www.ssdc.asi.it/

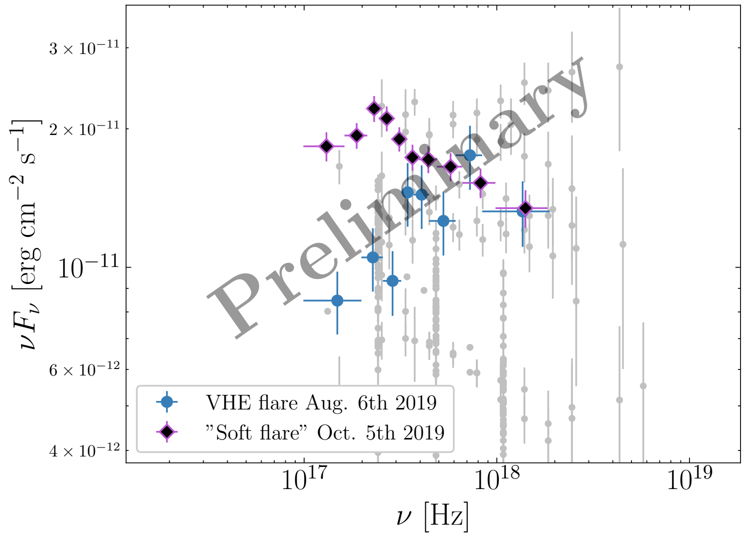

Figure 1: *Swift*-XRT SED during August 6$^{\text{th}}$ 2019 (blue markers) and October 5$^{\text{th}}$ 2019 (violet diamond markers). Archival data are plotted in grey and are taken from the SSDC database. While the SED on August 6$^{\text{th}}$ 2019 show a simultaneous bright VHE flare, the observations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

[4] Perlman E. S., Stocke J. T., Schachter J. F., Elvis M., Ellingson E., Urry C. M., Potter M., et al., 1996, ApJS, 104, 251. doi:10.1086/192300

[5] Catanese M., Akerlof C. W., Badran H. M., Biller S. D., Bond I. H., Boyle P. J., Bradbury S. M., et al., 1998, ApJ, 501, 616. doi:10.1086/305857

[6] Albert J., Aliu E., Anderhub H., Antoranz P., Armada A., Baixeras C., Barrio J. A., et al., 2007, ApJ, 662, 892. doi:10.1086/518431

[7] Acciari V. A., Aliu E., Arlen T., Aune T., Beilicke M., Benbow W., Boltuch D., et al., 2011, ApJ, 738, 169. doi:10.1088/0004-637X/738/2/169

[8] Allen C., Archambault S., Archer A., Benbow W., Bird R., Bourbeau E., Brose R., et al., 2017, MNRAS, 471, 2117. doi:10.1093/mnras/stx1756

[9] Ajello M., Angioni R., Axelsson M., Ballet J., Barbiellini G., Bastieri D., Becerra Gonzalez J., et al., 2020, ApJ, 892, 105. doi:10.3847/1538-4357/ab791e

[10] Padovani P., Giommi P., 1995, ApJ, 444, 567. doi:10.1086/175631

[11] Giommi P., Padovani P., Perlman E., 2000, MNRAS, 317, 743. doi:10.1046/j.1365-8711.2000.03353.x

[12] Gazeas K., 2016, RMxAC, 48, 22

[13] Richards J. L., Max-Moerbeck W., Pavlidou V., King O. G., Pearson T. J., Readhead A. C. S., Reeves R., et al., 2011, ApJS, 194, 29. doi:10.1088/0067-0049/194/2/29

Acknowledgments

We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The financial support of the German BMBF, MPG and HGF; the Italian INFN and INAF; the Swiss National Fund SNF; the grants PID2019-104114RB-C31, PID2019-104114RB-C32, PID2019-104114RB-C33, PID2019-105510GB-C31, PID2019-107847RB-C41, PID2019-107847RB-C42, PID2019-107847RB-C44, PID2019-107988GB-C22 funded by the Spanish MCIN/AEI/ 10.13039/501100011033; the Indian Department of Atomic Energy; the Japanese ICRR, the University of Tokyo, JSPS, and MEXT; the Bulgarian Ministry of Education and Science, National RI Roadmap Project DO1-400/18.12.2020 and the Academy of Finland grant nr. 320045 is gratefully acknowledged. This work was also been supported by Centros de Excelencia "Severo Ochoa" y Unidades "María de Maeztu" program of the Spanish MCIN/AEI/ 10.13039/501100011033 (SEV-2016-0588, CEX2019-000920-S, CEX2019-000918-M, CEX2021-001131-S, MDM-2015-0509-18-2) and by the CERCA institution of the Generalitat de Catalunya; by the Croatian Science Foundation (HrZZ) Project IP-2016-06-9782 and the University of Rijeka Project uniri-prirod-18-48; by the Deutsche Forschungsgemeinschaft (SFB1491 and SFB876); the Polish Ministry Of Education and Science grant No. 2021/WK/08; and by the Brazilian MCTIC, CNPq and FAPERJ. A.A.E and D.P acknowledge support from the Deutsche Forschungs gemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC-2094 – 390783311. This work made use of data from the *NuSTAR* mission, a project led by the California Institute of Technology, managed by the Jet Propulsion Laboratory, and funded by the National Aeronautics and Space Administration. We thank the *NuSTAR* Operations, Software, and Calibration teams for support with the execution and analysis of these observations. This research has made use of the *NuSTAR* Data Analysis Software (NuSTARDAS) jointly developed by the ASI Science Data Center (ASDC; Italy) and the California Institute of Technology (USA). This research has also made use of the XRT Data Analysis Software (XRTDAS) developed under the responsibility of the ASI Science Data Center (ASDC), Italy. The Abastumani team acknowledges financial support by the Shota Rustaveli NSF of Georgia under contract FR-19-6174. The R-band photometric data from the University of Athens Observatory (UOAO) were obtained after utilizing the robotic and remotely controlled instruments at the facilities [12]. The research at Boston University was supported in part by NASA Fermi GI grant 80NSSC22K1571 and U.S. National Science Foundation grant AST-2108622. This study was based (in part) on observations conducted using the 1.8 m Perkins Telescope Observatory (PTO) in Arizona (USA), which is owned and operated by Boston University. This research was partially supported by the Bulgarian National Science Fund of the Ministry of Education and Science under grants KP-06-H38/4 (2019), KP-06-KITAJ/2 (2020) and KP-06-H68/4 (2022). The Skinakas Observatory is a collaborative project of the University of Crete, the Foundation for Research and Technology – Hellas, and the Max-Planck-Institut für Extraterrestrische Physik. GD, OV, MDJ and MS acknowledge support by the Astronomical station Vidojevica, funding from the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (contract No. 451-03-47/2023-01/200002), by the EC through project BELISSIMA (call FP7-REGPOT-2010-5, No. 265772), the observing and financial grant support from the Institute of Astronomy and Rozhen NAO BAS through the bilateral SANU-BAN joint research project GAIA ASTROMETRY AND FAST VARIABLE ASTRONOMICAL OBJECTS, and support by the SANU project F-187. This paper used observations made with the IAC-80 telescope operated on the island of Tenerife by the Instituto de Astrofísica de Canarias in the Spanish Observatorio del Teide and also observations made with the LCOGT 0.4 m telescope network, one of whose nodes is located in the Spanish Observatorio del Teide. This research has made use of data from the OVRO 40-m monitoring program [13], supported by private funding from the California Institute of Technology and the Max Planck Institute for Radio Astronomy, and by NASA grants NNX08AW31G, NNX11A043G, and NNX14AQ89G and NSF grants AST-0808050 and AST-1109911. S.K. acknowledges support from the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation program under grant agreement No. 771282.

Full Authors List: MAGIC Collaboration

H. Abe[1], S. Abe[1], J. Abhir[2], V. A. Acciari[3], I. Agudo[4], T. Aniello[5], S. Ansoldi[6,46], L. A. Antonelli[5], A. Arbet Engels[7], C. Arcaro[8], M. Artero[9], K. Asano[1], D. Baack[10], A. Babić[11], A. Baquero[12], U. Barres de Almeida[13], J. A. Barrio[12], I. Batković[8], J. Baxter[1], J. Becerra González[3], W. Bednarek[14], E. Bernardini[8], M. Bernardos[4], J. Bernete[15], A. Berti[7], J. Besenrieder[7], C. Bigongiari[5], A. Biland[2], O. Blanch[9], G. Bonnoli[5], Ž. Bošnjak[11], I. Burelli[6], G. Busetto[8], A. Campoy-Ordaz[16], A. Carosi[5], R. Carosi[17], M. Carretero-Castrillo[18], A. J. Castro-Tirado[4], G. Ceribella[7], Y. Chai[7], R. Chatterjee[35], A. Chilingarian[19], A. Cifuentes[15], S. Cikota[11], E. Colombo[3], J. L. Contreras[12], J. Cortina[15], S. Covino[5], F. D'Ammando[5], G. D'Amico[20], V. D'Elia[5], P. Da Vela[17,47], F. Dazzi[5], A. De Angelis[8], B. De Lotto[6], A. Del Popolo[21], M. Delfino[9,48], J. Delgado[9,48], C. Delgado Mendez[15], D. Depaoli[22], F. Di Pierro[22], L. Di Venere[23], D. Dominis Prester[24], A. Donini[5], D. Dorner[25], M. Doro[8], D. Elsaesser[10], G. Emery[26], J. Escudero[4], L. Fariña[9], A. Fattorini[10], L. Foffano[5], L. Font[16], S. Fröse[10], S. Fukami[2], Y. Fukazawa[27], R. J. García López[3], M. Garczarczyk[28], S. Gasparyan[29], M. Gaug[16], J. G. Giesbrecht Paiva[13], N. Giglietto[23], F. Giordano[23], P. Gliwny[14], N. Godinović[30], R. Grau[9], D. Green[7], J. G. Green[7], D. Hadasch[1], A. Hahn[7], T. Hassan[15], L. Heckmann[7,49], J. Herrera[3], D. Hrupec[31], M. Hütten[1], R. Imazawa[27], T. Inada[1], R. Iotov[25], K. Ishio[14], I. Jiménez Martínez[15], J. Jormanainen[32], D. Kerszberg[9], G. W. Kluge[20,50], Y. Kobayashi[1], P. M. Kouch[32], H. Kubo[1], J. Kushida[33], M. Láinez Lezáun[12], A. Lamastra[5], D. Lelas[30], F. Leone[5], E. Lindfors[32], L. Linhoff[10], S. Lombardi[5], F. Longo[6,51], R. López-Coto[4], M. López-Moya[12], A. López-Oramas[3], S. Loporchio[23], A. Lorini[34], E. Lyard[26], B. Machado de Oliveira Fraga[13], P. Majumdar[35], M. Makariev[36], G. Maneva[36], N. Mang[10], M. Manganaro[24], S. Mangano[15], K. Mannheim[25], M. Mariotti[8], M. Martínez[9], M. Martínez-Chicharro[15], A. Mas-Aguilar[12], D. Mazin[1,52], S. Menchiari[34], S. Mender[10], S. Mićanović[24], D. Miceli[8], T. Miener[12], J. M. Miranda[34], R. Mirzoyan[7], M. Molero González[3], E. Molina[3], H. A. Mondal[35], A. Moralejo[9], D. Morcuende[12], T. Nakamori[37], C. Nanci[5], L. Nava[5], V. Neustroev[38], L. Nickel[10], M. Nievas Rosillo[3], C. Nigro[9], L. Nikolić[34], K. Nilsson[32], K. Nishijima[33], T. Njoh Ekoume[3], K. Noda[39], S. Nozaki[7], Y. Ohtani[1], T. Oka[40], A. Okumura[41], J. Otero-Santos[3], S. Paiano[5], M. Palatiello[6], D. Paneque[7], R. Paoletti[34], J. M. Paredes[18], L. Pavletić[24], D. Pavlović[24], M. Persic[6,53], M. Pihet[8], G. Pirola[7], F. Podobnik[34], P. G. Prada Moroni[17], E. Prandini[8], G. Principe[6], C. Priyadarshi[9], C. Raiteri[5], W. Rhode[10], M. Ribó[18], J. Rico[9], C. Righi[5], N. Sahakyan[29], T. Saito[1], S. Sakurai[1], K. Satalecka[32], F. G. Saturni[5], B. Schleicher[25], K. Schmidt[10], F. Schmuckermaier[7], J. L. Schubert[10], T. Schweizer[7], A. Sciaccaluga[5], J. Sitarek[14], V. Sliusar[26], D. Sobczynska[14], A. Spolon[8], A. Stamerra[5], J. Strišković[31], D. Strom[7], M. Strzys[1], Y. Suda[27], T. Surić[42], S. Suutarinen[32], H. Tajima[41], M. Takahashi[41], R. Takeishi[1], F. Tavecchio[5], P. Temnikov[36], K. Terauchi[40], T. Terzić[24], M. Teshima[7,54], L. Tosti[43], S. Truzzi[34], A. Tutone[5], S. Ubach[16], J. van Scherpenberg[7], M. Vazquez Acosta[3], S. Ventura[34], V. Verguilov[36], I. Viale[8], C. F. Vigorito[22], V. Vitale[44], I. Vovk[1], R. Walter[26], M. Will[7], C. Wunderlich[34], T. Yamamoto[45],

[1] Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan
[2] ETH Zürich, CH-8093 Zürich, Switzerland
[3] Instituto de Astrofísica de Canarias and Dpto. de Astrofísica, Universidad de La Laguna, E-38200, La Laguna, Tenerife, Spain
[4] Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, Spain
[5] National Institute for Astrophysics (INAF), I-00136 Rome, Italy
[6] Università di Udine and INFN Trieste, I-33100 Udine, Italy
[7] Max-Planck-Institut für Physik, D-80805 München, Germany
[8] Università di Padova and INFN, I-35131 Padova, Italy
[9] Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain
[10] Technische Universität Dortmund, D-44221 Dortmund, Germany
[11] Croatian MAGIC Group: University of Zagreb, Faculty of Electrical Engineering and Computing (FER), 10000 Zagreb, Croatia
[12] IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain
[13] Centro Brasileiro de Pesquisas Físicas (CBPF), 22290-180 URCA, Rio de Janeiro (RJ), Brazil
[14] University of Lodz, Faculty of Physics and Applied Informatics, Department of Astrophysics, 90-236 Lodz, Poland
[15] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain
[16] Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
[17] Università di Pisa and INFN Pisa, I-56126 Pisa, Italy
[18] Universitat de Barcelona, ICCUB, IEEC-UB, E-08028 Barcelona, Spain
[19] Armenian MAGIC Group: A. Alikhanyan National Science Laboratory, 0036 Yerevan, Armenia
[20] Department for Physics and Technology, University of Bergen, Norway
[21] INFN MAGIC Group: INFN Sezione di Catania and Dipartimento di Fisica e Astronomia, University of Catania, I-95123 Catania, Italy
[22] INFN MAGIC Group: INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy
[23] INFN MAGIC Group: INFN Sezione di Bari and Dipartimento Interateneo di Fisica dell'Università e del Politecnico di Bari, I-70125 Bari, Italy
[24] Croatian MAGIC Group: University of Rijeka, Faculty of Physics, 51000 Rijeka, Croatia
[25] Universität Würzburg, D-97074 Würzburg, Germany
[26] University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland
[27] Japanese MAGIC Group: Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan
[28] Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany
[29] Armenian MAGIC Group: ICRANet-Armenia, 0019 Yerevan, Armenia

[30] Croatian MAGIC Group: University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), 21000 Split, Croatia
[31] Croatian MAGIC Group: Josip Juraj Strossmayer University of Osijek, Department of Physics, 31000 Osijek, Croatia
[32] Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, University of Turku, FI-20014 Turku, Finland
[33] Japanese MAGIC Group: Department of Physics, Tokai University, Hiratsuka, 259-1292 Kanagawa, Japan
[34] Università di Siena and INFN Pisa, I-53100 Siena, Italy
[35] Saha Institute of Nuclear Physics, A CI of Homi Bhabha National Institute, Kolkata 700064, West Bengal, India
[36] Inst. for Nucl. Research and Nucl. Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria
[37] Japanese MAGIC Group: Department of Physics, Yamagata University, Yamagata 990-8560, Japan
[38] Finnish MAGIC Group: Space Physics and Astronomy Research Unit, University of Oulu, FI-90014 Oulu, Finland
[39] Japanese MAGIC Group: Chiba University, ICEHAP, 263-8522 Chiba, Japan
[40] Japanese MAGIC Group: Department of Physics, Kyoto University, 606-8502 Kyoto, Japan
[41] Japanese MAGIC Group: Institute for Space-Earth Environmental Research and Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, 464-6801 Nagoya, Japan
[42] Croatian MAGIC Group: Ruđer Bošković Institute, 10000 Zagreb, Croatia
[43] INFN MAGIC Group: INFN Sezione di Perugia, I-06123 Perugia, Italy
[44] INFN MAGIC Group: INFN Roma Tor Vergata, I-00133 Roma, Italy
[45] Japanese MAGIC Group: Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[46] also at International Center for Relativistic Astrophysics (ICRA), Rome, Italy
[47] now at Institute for Astro- and Particle Physics, University of Innsbruck, A-6020 Innsbruck, Austria
[48] also at Port d'Informació Científica (PIC), E-08193 Bellaterra (Barcelona), Spain
[49] also at Institute for Astro- and Particle Physics, University of Innsbruck, A-6020 Innsbruck, Austria
[50] also at Department of Physics, University of Oslo, Norway
[51] also at Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[52] Max-Planck-Institut für Physik, D-80805 München, Germany
[53] also at INAF Padova
[54] Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan