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Upper limits on the very high energy emission from GRBs observed by MAGIC

Francesco Longo,[a,b,c,*] **Alessio Berti,**[d] **Zeljka Bosnjak,**[e] **Alice Donini,**[b,f,g] **Satoshi Fukami,**[h] **Jarred Gershon Green,**[i] **Davide Miceli,**[b,f,j] **Elena Moretti,**[g] **Lara Nava**[b,c,k] **and Koji Noda**[h] **on behalf of the MAGIC Collaboration**[†]

[a] *University of Trieste, Department of Physics, via Valerio 2, Trieste, Italy*
[b] *INFN, Sezione di Trieste,via Valerio 2, Trieste, Italy*
[c] *Institute for Fundamental Physics of the Universe (IFPU), via Beirut 12, Trieste, Italy*
[d] *Max Planck Institute for Physics, Föhringer Ring 6, Munich, Germany*
[e] *University of Zagreb, Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia*
[f] *University of Udine, Dipartimento di Scienze Matematiche, Informatiche e Fisiche via delle Scienze 206, Udine, Italy*
[g] *Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), Bellaterra (Barcelona), Spain*
[h] *Institute for Cosmic Ray Research, The University of Tokyo, Kashiwanoha 5-1-5, Kashiwa, Japan*
[i] *Osservatorio Astronomico di Roma, INAF, Via Frascati, 33, Monte Porzio Catone (RM), Italy*
[j] *Laboratoire d'Annecy de Physique des Particules (LAPP), CNRS-IN2P3, 9 Chemin de Bellevue - BP 110, Annecy Cedex, France*
[k] *Osservatorio Astronomico di Brera, INAF, via E. Bianchi 46, Merate (LC), Italy*

E-mail: francesco.longo@ts.infn.it

The MAGIC collaboration has developed a dedicated observational strategy to repoint rapidly towards gamma-ray bursts (GRBs). In this contribution we present the information extracted from the large sample of the GRBs observed by MAGIC from 2013 to 2019. None of these GRBs were significantly detected, and this study aims to shed light on the reasons behind those non-detections. The same strategy had led to the successful detection of two GRBs at Very High Energies (VHE, E > 100 GeV). We describe the details of the MAGIC GRB observational procedure and the general properties of each observed GRB. The lack of detection can be attributed either to unfavourable conditions or GRB intrinsic properties, such as the magnetic field's energy density, the bulk Lorentz factor, or the emitting region's size. For the presented sample of GRBs, we show the methods used to obtain flux upper limits in the VHE range, and propose physical implications of the non-detection of VHE emission. These results constitute an essential reference point to study the broadband emission of GRBs, and for the Cherenkov telescope community to organize future follow-ups of GRBs at VHE energies.

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[*] Presenter

[†] a complete list of the MAGIC Collaboration authors can be found at the end of the proceedings

1. Introduction

The possibility to detect the elusive component of VHE emission from GRBs has been one of key scientific goals of Cherenkov telescopes for decades. The detection of such a component from a gamma-ray burst would have indeed several scientific benefits (see e.g. [1]). A new window would be opened on the GRB emission mechanisms. We could put constraints on the particle acceleration mechanisms and the GRB jet composition as as well as the absorption of TeV photons by the Extragalactic Background Light (EBL). The search for VHE GRBs has been one of the most difficult challenges for all very high energy telescopes, given the cosmological nature and the random occurrence of these sources in the sky. This research required the development of alert systems and analysis methods adapted to non-standard observation conditions to avoid losing the few opportunities for revealing the most interesting events ([2, 3]). The situation has evolved rapidly in the past few years with the announcement by MAGIC ([4–7]) and H.E.S.S. ([8, 9]) of the detection of four GRBs at energies greater than one hundred GeV. They were followed, more recently, by the announcement of the observation of other GRBs at very high energies, albeit with different significance ([10, 11]). Having achieved the aim of revealing the first GRBs at TeV energies, the research now focuses on identifying whether there are common characteristics in GRBs showing emission components at the highest energies. This contribution describes the ongoing search for GRB detection by MAGIC, and highlights the results on all the non detected GRBs after a significant upgrade of the MAGIC automated alert system in the year 2013.

2. The MAGIC GRB follow-up procedure and the GRB sample

The MAGIC telescopes were designed in order to perform fast follow-up observations of GRBs, with the scope of detecting a VHE gamma-ray signal from these sources. First of all, the telescopes have a very light carbon fiber structure, so that they can slew with a remarkable speed of $7\,^{\circ}\,\mathrm{s}^{-1}$. In that way, MAGIC can perform a 180° rotation in less than 30 s. A second asset is the low energy threshold. MAGIC can reach an energy threshold as low as 50 GeV at zenith, or even 30 GeV using the so-called Sum-Trigger-II ([12]). This is particularly important given the strong VHE flux absorption that is expected for such distant sources as GRBs. Finally, the high sensitivity at low energies is crucial to detect transient emission in short timescales.

However, given the small field of view of 3.5°, which is typical for an IACT, MAGIC needs to rely on external triggers in order to perform GRB follow-up. For this purpose, an automatic alert system (AAS) was developed. Its main tasks are to receive GRB (and other transients) alerts from the Gamma-ray Coordinates Network (GCN), validate them, and check if the target is visible from the MAGIC site, according to predefined criteria. In the case of an observable alert, an automatic procedure is in place, with no human-in-the-loop to reduce latency and possible issues as much as possible. Following the procedure, the ongoing observation is stopped and the telescopes start slewing to the GRB position. In the meanwhile, other subsystems (data acquisition, mirrors, trigger system) are configured to start the new observation as soon as the telescopes reach the target. The observation is performed in the wobble pointing mode, so that the standard IACT analysis techniques can be adopted. Usually the observation of GRBs is carried on for 4 h. The people in charge of following GRB observations together with the onsite operators, the so-called

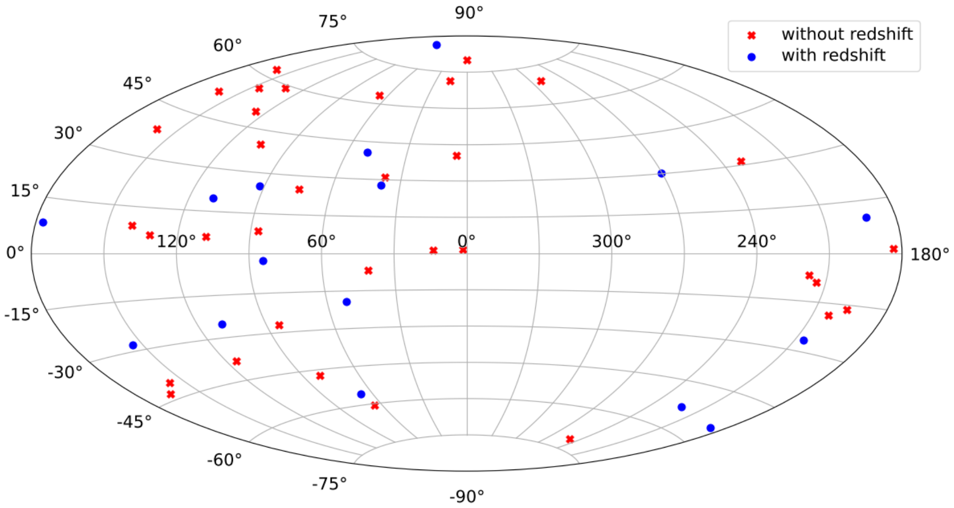

Figure 1: Sky map of all the GRBs followed by MAGIC from 2013 to 2019

Burst Advocates (BAs), can decide to increase or decrease observation time according to additional information coming from different channels.

Thanks to this automatic procedure, MAGIC could follow-up more than 130 GRBs starting from 2005. Up to 2013, GRB observations resulting from the automatic procedure were carried out with ON pointing mode. In this observation mode, an equal amount of OFF data must be taken for background estimation. In 2013, the automatic procedure was upgraded so that wobble pointing could be used during GRB follow-up observations. The other major update was related to the data acquisition system, which is not stopped but only reconfigured during the automatic procedure, hence reducing the number of possible failures.

For this reason, we focus this study on GRBs observed by MAGIC from the upgrade of the automatic procedure up to the end of 2019. All the 50 GRBs observed in this time period are shown in the skymap of Figure 1. In particular for this study we consider those GRBs without any (hint of) detection in the VHE range. According to this criterion, GRB 160821B [10] and GRB 190114C [5] are excluded from this study. Also GRB 190829A [9], detected by H.E.S.S., is not included here in order to have a dedicated study of this GRB. With these exclusions, the number of GRBs followed-up by MAGIC in the above mentioned interval is 47. However, not all of these GRBs were finally analyzed. Some of them were observed under bad weather conditions (characterised by low atmospheric transmission, high humidity or strong winds), or just with one telescope, or with a very high level of the night sky background light due to strong moonlight (e.g. needing the usage of reduced high voltage or moon filters, see [13]) reducing drastically the sensitivity of the instrument.

Therefore we focus on the GRBs meeting these quality criteria, which are 41. In particular, the VHE data for GRBs observed at low zenith, with relatively small delay with respect to the GRB onset and with a redshift estimate were compared to data available in other bands, especially in the X-ray band, as described in Section 3.

3. GRB Upper Limits calculation

Data analyses of GRBs have been performed by means of the MAGIC standard software package MARS [14]. The sample comprises of GRBs observed in different observational conditions including also observations during moderate moonlight or not optimal weather conditions. Therefore, dedicated event-selection criteria have been used during the analysis of these GRBs. Higher image cleaning levels with respect to the standard ones have been used in case of observations in presence of Moon as described in [13]. Corrections to estimated energy and effective collection area have been derived in case of not optimal weather conditions thanks to the information provided by the LIDAR facility[15, 16].

Given the lack of a significant signals, Upper Limits (ULs) on the deabsorbed photon flux emitted in the VHE domain were derived. In MAGIC standard data analysis chain, ULs are calculated with the method of Rolke et al. [17] with a 95% Confidence Level (CL) and a total systematic uncertainty of 30%. Several theoretical assumptions have been driving the UL calculation. The deabsorbed gamma-ray differential photon spectrum was presumed to be described by a power law behaviour $dN/dE = E^{-\alpha}$. We assumed the values 1.6 and 2.2 for the photon index α because such values reproduce the asymptotic behaviours expected in the SSC spectrum when the peak of the emission is found to be below or above the GeV-TeV band. A confirmation of the validity of this approach is found also from the best fit spectral parameters calculated from the observations of GRB 180720B [8] and GRB 190114C [6] detected in the VHE domain. For the estimation of the EBL absorption two different models have been adopted: Franceschini et al. (2018) [18], and Gilmore et al. (2012) [19]. For the GRBs with unknown redshift a value of $z = 2$ has been assumed for long GRBs and $z = 0.5$ for short GRBs. Indeed, these are the current median redshift values of the *Swift* long and short GRB population [20].

For a subsample of GRBs showing promising features for the VHE band and a good X-ray coverage contemporaneous to the MAGIC observational window, we provided a comparison between the estimated MAGIC ULs and the soft X-ray flux. The current GRB detections in the VHE domain have shown to have an intimate connection with the soft X-ray band emission in terms of emitted power and responsible radiation mechanisms. GRBs with known redshift $z < 2$ were first selected. Then, the MAGIC ULs on the intrinsic flux have been estimated only for the time intervals and the energetic ranges which assure that the total systematic uncertainty of the computed UL is within 30%. We considered several different values of the low energy edge of the flux-integration window E_{min}, and we compared the corresponding effective area in order to assure that condition on the total systematic uncertainty was preserved. We choose the minimum value of E_{min} for which the estimated effective area varied less than 30% when shifting the low energy edge of the flux-integration window by a factor ± 15%. The upper energy edge E_{max} was fixed to 1.5 TeV in the rest frame. This value is chosen considering that the highest photon energies observed by MAGIC from GRB 190114C are $\sim$ 1 TeV (observer frame, corresponding to $\sim$ 1.5 TeV in the rest frame).

Some GRBs in the sample were also observed in the medium-high zenithal range (Zd>40). When including these data for GRBs with $z > 1$ (which constitute the majority of our sample), the extremely steep observed spectrum due to the high EBL absorption does not allow to fullfill the condition on the systematic uncertainty. If the observations were performed with long delay with respect to the GRB trigger time, we decided to exclude this time interval from the UL calculation. We include only the low-medium zenithal angle observations which assure that the total systematic uncertainty of the resulting ULs were below 30%. As a result, a set of four ULs were derived following the assumptions on the assumed deabsorbed photon spectrum and on the chosen EBL models.

4. Upper Limits implications

The derived VHE ULs of the most intriguing events, including also the collection of simultaneous X-ray data, are useful to draw conclusions on the properties of the VHE emission component. If the drived ULs are found at the same level as the contemporanous X-ray flux, this indicates a VHE energy budget similar to the one in X-rays. Moreover, combined multi-wavelength afterglow observations can be useful to constrain the unknown properties of the external forward shock scenario. It is possible to investigate the amount of the amplification of the magnetic field and the portion of energy given to the accelerated particles, or the density and the properties of the ambient medium surrounding the GRB explosion. The most credible radiation mechanisms, namely the synchrotron and synchrotron-self Compton (SSC) emission can also be tested. Further information on the performed studies will be found in the upcoming publication.

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Full Authors List: MAGIC Collaboration

V. A. Acciari[1], S. Ansoldi[2,41], L. A. Antonelli[3], A. Arbet Engels[4], M. Artero[5], K. Asano[6], D. Baack[7], A. Babić[8], A. Baquero[9], U. Barres de Almeida[10], J. A. Barrio[9], I. Batković[11], J. Becerra González[1], W. Bednarek[12], L. Bellizzi[13], E. Bernardini[14], M. Bernardos[11], A. Berti[15], J. Besenrieder[15], W. Bhattacharyya[14], C. Bigongiari[3], A. Biland[4], O. Blanch[5], H. Bökenkamp[7], G. Bonnoli[16], Ž. Bošnjak[8], G. Busetto[11], R. Carosi[17], G. Ceribella[15], M. Cerruti[18], Y. Chai[15], A. Chilingarian[19], S. Cikota[8], S. M. Colak[5], E. Colombo[1], J. L. Contreras[9], J. Cortina[20], S. Covino[3], G. D'Amico[15,42], V. D'Elia[3], P. Da Vela[17,43], F. Dazzi[3], A. De Angelis[11], B. De Lotto[2], M. Delfino[5,44], J. Delgado[5,44], C. Delgado Mendez[20], D. Depaoli[21], F. Di Pierro[21], L. Di Venere[22], E. Do Souto Espiñeira[5], D. Dominis Prester[23], A. Donini[2], D. Dorner[24], M. Doro[11], D. Elsaesser[7], V. Fallah Ramazani[25,45], A. Fattorini[7], M. V. Fonseca[9], L. Font[26], C. Fruck[15], S. Fukami[6], Y. Fukazawa[27], R. J. García López[1], M. Garczarczyk[14], S. Gasparyan[28], M. Gaug[26], N. Giglietto[22], F. Giordano[22], P. Gliwny[12], N. Godinović[29], J. G. Green[3], D. Green[15], D. Hadasch[6], A. Hahn[15], L. Heckmann[15], J. Herrera[1], J. Hoang[9,46], D. Hrupec[30], M. Hütten[15], T. Inada[6], K. Ishio[12], Y. Iwamura[6], I. Jiménez Martínez[20], J. Jormanainen[25], L. Jouvin[5], M. Karjalainen[1], D. Kerszberg[5], Y. Kobayashi[6], H. Kubo[31], J. Kushida[32], A. Lamastra[3], D. Lelas[29], F. Leone[3], E. Lindfors[25], L. Linhoff[7], S. Lombardi[3], F. Longo[2,47], R. López-Coto[11], M. López-Moya[9], A. López-Oramas[1], S. Loporchio[22], B. Machado de Oliveira Fraga[10], C. Maggio[26], P. Majumdar[33], M. Makariev[34], M. Mallamaci[11], G. Maneva[34], M. Manganaro[23], K. Mannheim[24], L. Maraschi[3], M. Mariotti[11], M. Martínez[5], D. Mazin[6,15], S. Menchiari[13], S. Mender[7], S. Mićanović[23], D. Miceli[2,49], T. Miener[9], J. M. Miranda[13], R. Mirzoyan[15], E. Molina[18], A. Moralejo[5], D. Morcuende[9], V. Moreno[26], E. Moretti[5], T. Nakamori[35], L. Nava[3], V. Neustroev[36], C. Nigro[5], K. Nilsson[25], K. Nishijima[32], K. Noda[6], S. Nozaki[31], Y. Ohtani[6], T. Oka[31], J. Otero-Santos[1], S. Paiano[3], M. Palatiello[2], D. Paneque[15], R. Paoletti[13], J. M. Paredes[18], L. Pavletić[23], P. Peñil[9], M. Persic[2,50], M. Pihet[15], P. G. Prada Moroni[17], E. Prandini[11], C. Priyadarshi[5], I. Puljak[29], W. Rhode[7], M. Ribó[18], J. Rico[5], C. Righi[3], A. Rugliancich[17], N. Sahakyan[28], T. Saito[6], S. Sakurai[6], K. Satalecka[14], F. G. Saturni[3], B. Schleicher[24], K. Schmidt[7], T. Schweizer[15], J. Sitarek[12], I. Šnidarić[37], D. Sobczynska[12], A. Spolon[11], A. Stamerra[3], J. Strišković[30], D. Strom[15], M. Strzys[6], Y. Suda[27], T. Surić[37], M. Takahashi[6], R. Takeishi[6], F. Tavecchio[3], P. Temnikov[34], T. Terzić[23], M. Teshima[15,6], L. Tosti[38], S. Truzzi[13], A. Tutone[3], S. Ubach[26], J. van Scherpenberg[15], G. Vanzo[1], M. Vazquez Acosta[1], S. Ventura[13], V. Verguilov[34], C. F. Vigorito[21], V. Vitale[39], I. Vovk[6], M. Will[15], C. Wunderlich[13], T. Yamamoto[40], and D. Zarić[29]

[1] Instituto de Astrofísica de Canarias and Dpto. de Astrofísica, Universidad de La Laguna, E-38200, La Laguna, Tenerife, Spain
[2] Università di Udine and INFN Trieste, I-33100 Udine, Italy
[3] National Institute for Astrophysics (INAF), I-00136 Rome, Italy
[4] ETH Zürich, CH-8093 Zürich, Switzerland
[5] Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology (BIST), E-08193 Bellaterra (Barcelona), Spain
[6] Japanese MAGIC Group: Institute for Cosmic Ray Research (ICRR), The University of Tokyo, Kashiwa, 277-8582 Chiba, Japan
[7] Technische Universität Dortmund, D-44221 Dortmund, Germany
[8] Croatian MAGIC Group: University of Zagreb, Faculty of Electrical Engineering and Computing (FER), 10000 Zagreb, Croatia
[9] IPARCOS Institute and EMFTEL Department, Universidad Complutense de Madrid, E-28040 Madrid, Spain
[10] Centro Brasileiro de Pesquisas Físicas (CBPF), 22290-180 URCA, Rio de Janeiro (RJ), Brazil
[11] Università di Padova and INFN, I-35131 Padova, Italy
[12] University of Lodz, Faculty of Physics and Applied Informatics, Department of Astrophysics, 90-236 Lodz, Poland
[13] Università di Siena and INFN Pisa, I-53100 Siena, Italy
[14] Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany
[15] Max-Planck-Institut für Physik, D-80805 München, Germany
[16] Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, 18008, Granada, 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] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain
[21] INFN MAGIC Group: INFN Sezione di Torino and Università degli Studi di Torino, I-10125 Torino, Italy
[22] INFN MAGIC Group: INFN Sezione di Bari and Dipartimento Interateneo di Fisica dell'Università e del Politecnico di Bari, I-70125 Bari, Italy
[23] Croatian MAGIC Group: University of Rijeka, Department of Physics, 51000 Rijeka, Croatia
[24] Universität Würzburg, D-97074 Würzburg, Germany
[25] Finnish MAGIC Group: Finnish Centre for Astronomy with ESO, University of Turku, FI-20014 Turku, Finland
[26] Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
[27] Japanese MAGIC Group: Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 739-8526 Hiroshima, Japan
[28] Armenian MAGIC Group: ICRANet-Armenia at NAS RA, 0019 Yerevan, Armenia
[29] Croatian MAGIC Group: University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), 21000 Split, Croatia
[30] Croatian MAGIC Group: Josip Juraj Strossmayer University of Osijek, Department of Physics, 31000 Osijek, Croatia
[31] Japanese MAGIC Group: Department of Physics, Kyoto University, 606-8502 Kyoto, Japan

[32] Japanese MAGIC Group: Department of Physics, Tokai University, Hiratsuka, 259-1292 Kanagawa, Japan
[33] Saha Institute of Nuclear Physics, HBNI, 1/AF Bidhannagar, Salt Lake, Sector-1, Kolkata 700064, India
[34] Inst. for Nucl. Research and Nucl. Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria
[35] Japanese MAGIC Group: Department of Physics, Yamagata University, Yamagata 990-8560, Japan
[36] Finnish MAGIC Group: Astronomy Research Unit, University of Oulu, FI-90014 Oulu, Finland
[37] Croatian MAGIC Group: Ruđer Bošković Institute, 10000 Zagreb, Croatia
[38] INFN MAGIC Group: INFN Sezione di Perugia, I-06123 Perugia, Italy
[39] INFN MAGIC Group: INFN Roma Tor Vergata, I-00133 Roma, Italy
[40] Japanese MAGIC Group: Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
[41] also at International Center for Relativistic Astrophysics (ICRA), Rome, Italy
[42] now at Department for Physics and Technology, University of Bergen, NO-5020, Norway
[43] now at University of Innsbruck
[44] also at Port d'Informació Científica (PIC), E-08193 Bellaterra (Barcelona), Spain
[45] now at Ruhr-Universität Bochum, Fakultät für Physik und Astronomie, Astronomisches Institut (AIRUB), 44801 Bochum, Germany
[46] now at Department of Astronomy, University of California Berkeley, Berkeley CA 94720
[47] also at Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[49] now at Laboratoire d'Annecy de Physique des Particules (LAPP), CNRS-IN2P3, 74941 Annecy Cedex, France
[50] also at INAF Trieste and Dept. of Physics and Astronomy, University of Bologna, Bologna, Italy