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FLUX UPPER LIMIT ON GAMMA-RAY EMISSION BY GRB 050713a FROM MAGIC TELESCOPE OBSERVATIONS

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ABSTRACT

The long-duration γ-ray burst GRB 050713a was observed by the MAGIC Telescope 40 s after the burst onset and followed up for 37 minutes, until twilight. The observation, triggered by a *Swift* alert, covered energies above ≈175 GeV. Using standard MAGIC analysis, no evidence of a γ-ray signal was found. As the redshift of the GRB was not measured directly, the flux upper limit estimated by MAGIC is still compatible with the assumption of an unbroken power-law spectrum extending from a few hundred keV to our energy range.

Subject headings: gamma rays: bursts — gamma rays: observations

Online material: color figures

1. INTRODUCTION

Observations of high-energy photons from γ-ray bursts (GRBs) have contributed much to a deeper understanding of the bursts' nature. The γ-ray emission observed by the Energetic Gamma-Ray Experiment Telescope (EGRET) (Hurley et al. 1994) suggests a power-law spectrum extending up to GeV energies. This favors an optically thin emission region and a nonthermal origin for the bursts. As excessive pair production could be suppressed in the presence of relativistic jets (Goodman 1986; Paczyński 1986), it has been concluded that relativistic beaming could play an important role in GRBs (Mészáros & Rees 1993). However, other models also point toward the presence of a strong thermal component in GRB spectra (Ryde 2004).

The observation of γ-rays at the highest energies is expected to have an important impact on the modeling of the emission processes, in particular for the early and late afterglow phases of GRBs. EGRET measurements generally show the presence of a hard, long-duration component (Dingus 1995), consistent with a simple extrapolation of the MeV spectrum into the high-energy γ-ray regime. Recently, an additional, delayed high-energy component of GRB 970417 was found with the TASC

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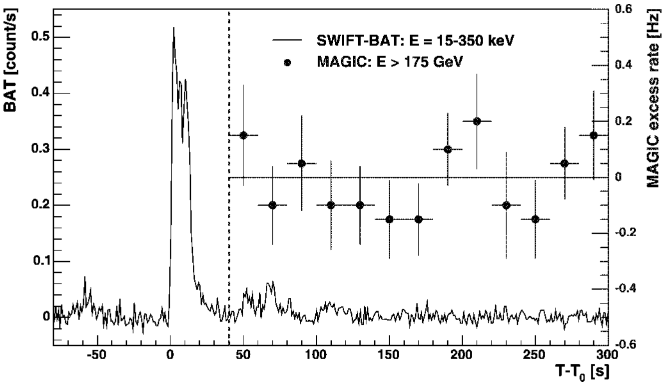

FIG. 1.—MAGIC excess event rate compared with *Swift* BAT observations. The dashed vertical line indicates the start of observations with the MAGIC Telescope; the prominent peak seen by BAT occurred before MAGIC observations started. [*See the electronic edition of the Journal for a color version of this figure.*]

detector of EGRET (González et al. 2003). Several models predict GeV–TeV emission lasting up to the early afterglow (Pe'er & Waxman 2004; Dermer & Atoyan 2004). Because of the extremely high energies attainable inside relativistic jets, GRBs are potential sources of very high energy (VHE) cosmic rays (Waxman 1995; Vietri 1995), which can in turn produce hadronic showers containing VHE γ-rays. Other theoretical models predict no emission above a few MeV (Lazzati et al. 2004) or predict strong emission up to GeV energies but no emission above 10 GeV (Stern & Poutanen 2004). Therefore, measurements at this energy range can be used to test all these competing models. However, as most of the observed GRBs occur at large redshift, strong attenuation of the VHE γ-ray flux is expected, as a result of the interaction with low-energy photons from the metagalactic radiation field (MRF) (Nikishov 1961; de Jager & Stecker 2002). Knowledge of the redshift is, therefore, important for a precise interpretation. On the other hand, a detection of VHE γ-rays provides an indirect—and model-dependent—upper limit on a GRB's redshift, if some knowledge of the MRF is assumed.

Several observations of GRBs at energies above 100 GeV have been attempted (Götting & Horns 2003; Zhou 2003), without showing any indication of a signal. This is due to relatively low sensitivity, as in satellite-borne detectors, and high energy thresholds, as in the previous generation of Cerenkov telescopes or in particle detector arrays. Up to now, only upper limits on the prompt or delayed emission of GRBs have been set by Whipple (Connaughton et al. 1997), MILAGRO (see Atkins et al. 2005 and references therein), and STACEE (Jarvis et al. 2005). STACEE, in the same energy region as is attainable by MAGIC, was able to follow GRB 050607 from 3 minutes 11 s for 1150 s and set an upper limit on its flux of $\Phi(>100\ \mathrm{GeV}) < 4.1 \times 10^{-9}\ \mathrm{cm^{-2}\ s^{-1}} \approx 6$ crabs [1 crab $= 1.5 \times 10^{-6} E(\mathrm{GeV})^{-2.58}$ photons cm^{-2} s^{-1} GeV^{-1}].

The situation may change with the new generation of Cerenkov telescopes, which achieve a better flux sensitivity and a lower energy threshold. Nevertheless, as their small fields of view allow prompt observations only by virtue of serendipitous detection, they have to rely on an external trigger, such as that provided by automated satellite link to the GRB Coordinates Network (GCN),[21] which broadcasts the coordinates of events triggered and selected by dedicated satellite detectors.

Among the new Cerenkov telescopes, MAGIC (Mirzoyan 2005) is best suited for the detection of the prompt emission of GRBs, because of its low energy threshold, large effective area, and, in particular, its capability for fast slewing (Bretz et al. 2003). The low trigger threshold, currently 50 GeV at zenith, should allow the observation of GRBs even at large redshift, as lower energy radiation can effectively reach Earth without interacting much with the MRF. Moreover, in its fast-slewing mode, MAGIC can be repositioned within $\lesssim$30 s to any position on the sky; in case of a target-of-opportunity alert by GCN, an automated procedure takes only few seconds to terminate any pending observation, validate the incoming signal, and start slewing toward the GRB position. Extrapolating BATSE-observed GRB spectra to the VHE with an unbroken power law of index as listed in the BATSE catalog, MAGIC is predicted to detect about one GRB per year at the 5 σ level (Galante et al. 2003).

In this Letter, we report on the analysis of data collected on GRB 050713a during its prompt emission phase and for the following 37 minutes.

2. MAGIC OBSERVATION

On 2005 July 13 at 04:29:02 UT, the Burst Alert Telescope (BAT) on board *Swift* detected a burst located at J2000 R.A. $= 21^{\mathrm{h}}22^{\mathrm{m}}09^{\mathrm{s}}$, decl. $= +77°04'20''$ (undertainty $\pm 3''$; Falcone et al. 2005). The MAGIC alert system received and validated the alert 12 s after the burst, and data taking started 40 s after the initial burst time (T_0) (Galante et al. 2005).

The burst was classified by *Swift* as a bright burst with a duration of $T_{90} = 70 \pm 10$ s. The brightest part of the keV emission occurred within $T_0 + 20$ s; three smaller peaks followed at $T_0 + 50$ s, $T_0 + 65$ s, and $T_0 + 105$ s, while a *preburst* peak took place at $T_0 - 60$ s. (see Fig. 1). The spectrum, over the interval from $T_0 - 70$ s to $T_0 + 121$ s, can be fitted with a power law with photon index -1.58 ± 0.07 and yields a fluence of 9.1×10^{-6} ergs cm^{-2} in the 15–350 keV range (Palmer et al. 2005). The burst also triggered the Konus detector on the *Wind* satellite (Golenetskii et al. 2005), which measured the spectrum of the burst during the first 16 s, the duration of the first big peak reported by *Swift*.

2.1. *Data Set and Analysis*

In the local coordinate system of MAGIC, GRB 050713a was located at an azimuth angle of $-6°$ (near north) and a zenith angle of 50°. The sky region of the burst was observed for 37 minutes, until twilight (ON data). Between $T_0 + 665$ s and $T_0 + 686$ s, data taking was interrupted for technical reasons. A total amount of 258,250 atmospheric showers, mainly background, were recorded. In order to evaluate the background contamination in the data, the GRB position was observed again 48 hr later (OFF data).

Data were analyzed using the MAGIC standard software (Bretz et al. 2005; Gaug et al. 2005). For optimizing γ/hadron separation, we simulated 10^5 γ-ray events with zenith angle ranging between 47° and 52°, energy greater than 10 GeV, and an energy distribution following a power-law spectrum of index $\beta_\gamma = -2.6$. This sample was analyzed in the same way as the data and was used for the calculation of the collection area, the sensitivity, and the energy estimation. After applying all selection criteria, the sample peaked at around 250 GeV, which we define as our telescope threshold at this zenith angle.

The data were processed using the standard Hillas analysis (Hillas 1985; Fegan 1997). Gamma/hadron separation is per-

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[21] See http://gcn.gsfc.nasa.gov.

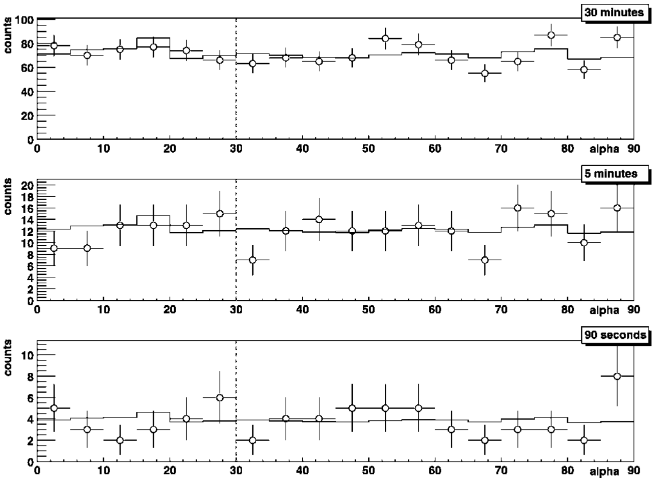

FIG. 2.—Hillas "alpha" distributions of events with 175 GeV $< E <$ 225 GeV for three different time intervals starting at $T = T_0 + 40$ s: 30 minutes (*top*), 5 minutes (*middle*), and 90 s (*bottom*). Circles refer to ON data, the solid line to OFF data. The dashed vertical line bounds the region where we would expect the γ-ray signal. [*See the electronic edition of the Journal for a color version of this figure*.]

formed by means of random forests (RF; Breiman 2001), a classification method that combines several parameters describing the shape of the image into a new parameter called *hadronness*, the final γ/hadron discriminator in our analysis. The simulated sample was used to optimize, as a function of energy, the cuts in hadronness. Also, the γ-ray energy was estimated using a RF approach, yielding a resolution of ≈30% at 200 GeV.

The parameter "alpha" of the Hillas analysis, which is related to the direction of the incoming shower, is used to evaluate the significance of a signal. If the telescope is directed at a pointlike γ-ray source, as a GRB is expected to be, the alpha-distribution of collected photons should peak at 0°, while it is uniform for isotropic background showers. According to simulations, the γ-ray signal at low energies may spread in a region defined conservatively by alpha-values of less than 30°. Figure 2 shows the alpha-distributions for the GRB 050713a and OFF data, divided into three subsets of time covering 90 s, 5 minutes, and 30 minutes, respectively. No evidence of excess in the signal region is seen.

2.2. *Time Analysis*

A second analysis searching for short-time variable γ-ray signals from GRB 050713a was performed in the 175 GeV $<$ $E <$ 225 GeV range. Figure 3 shows the number of excess events during the first 37 minutes after the burst, in intervals of 20 s. The number of expected background events in the signal region (*open circles*), estimated from the number of events in the region with alpha $>$ 30°, is constant, indicating stable experimental conditions. The number of excess events is stable and compatible with statistical fluctuations of the background. The same analysis was applied to the OFF data, with similar results.

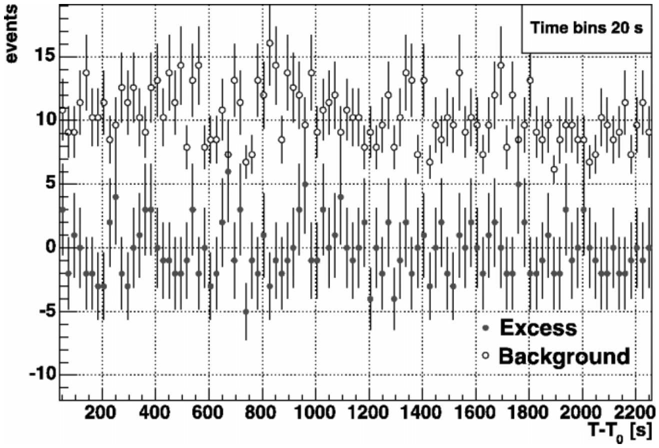

FIG. 3.—*Filled circles*, number of excess events for 20 s intervals in the 37 minute window after the burst; *open circles*, number of background events in the signal region. [*See the electronic edition of the Journal for a color version of this figure*.]

2.3. *Flux Upper Limits*

By analyzing the data collected during the prompt emission of GRB 050713a between $T_0 + 40$ s and $T_0 + 130$ s, we can set upper limits on its flux at 95% confidence level (see Rolke et al. 2005 for details). The upper limit can be used to constrain the prompt emission of the GRB in the VHE range. Since the observed spectrum is the convolution of the intrinsic spectrum and the MRF absorption, the limits on the former are thus necessarily model dependent.

First of all, we assumed the GRB spectrum extends to GeV energies following the Band function (Band et al. 1993): after the energy break, estimated by Konus/*Wind* to be at ∼355 keV, the flux follows a power law of spectral index $\beta = -2.5$, the mean value of the BATSE distribution (see Preece et al. 2000). In this hypothesis, we calculated the upper limit on the average flux in our energy range during the entire 90 s interval. These values are summarized in Table 1, and the lowest two energy bins are shown in Figure 4, together with the spectrum measured at lower energies by *Swift* and Konus/*Wind*.

It has to be noted, however, that according to the BAT data, only 10%–15% of the total burst fluence in the 100 keV region was released during the window of the MAGIC observations. This fraction of the flux is plotted in Figure 4 (*dashed line*).

TABLE 1

MAGIC UPPER LIMIT ON GRB 050713a BETWEEN $T_0 + 40$ s AND $T_0 + 130$ s

ENERGY (GeV)	EXCESS EVENTS UPPER LIMIT	EFF. AREA (10^8 cm^2)	FLUX UPPER LIMIT (10^{-9} ergs cm^{-2} s^{-1})			
			$z = 0$	$z = 0.2$	$z = 0.6$	$z = 1$
175–225	8.5	1.7	0.83 (7.6)	1.16	3.42	10.49
225–300	10.4	3.4	0.45 (4.8)	1.07	4.63	19.32
300–400	6.0	5.3	0.37 (3.8)	1.35	13.20	95.45
400–1000	4.3	6.5	0.13 (3.3)	0.68	25.11	293.18

NOTE.—Limits (95% confidence) include a systematic uncertainty of 30% and have been corrected for the photon absorption by the extragalactic background light for different redshift values z. For $z =$ 0 (no correction applied), the flux upper limits are also given in crab units (in parentheses).

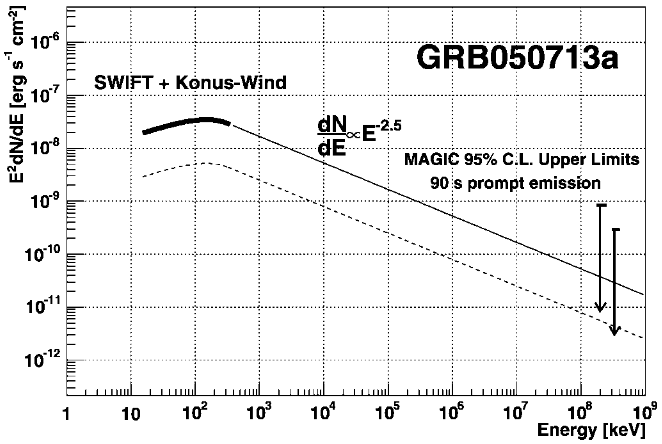

FIG. 4.—Upper limits set by MAGIC on GRB 050713a with no redshift correction applied (see text). The solid line is the flux measured by *Swift* averaged over the burst T_{90}, and the energy break is estimated using Konus/*Wind* data. The dashed line represents the fraction of the flux emitted between $T_0 + 40$ s and $T_0 + 130$ s.

Adopting a semiempirical model for the cosmologically evolving MRF (Kneiske et al. 2004), we derive the unfolded flux upper limits for various redshift values shown in Table 1.

3. CONCLUSIONS

MAGIC was able to observe part of the prompt emission phase of a GRB in response to the alert system provided by the *Swift* satellite. No excess above 175 GeV was detected during either the prompt emission phase or the following 37 minutes. We have derived an upper limit to the γ-ray flux between 175 and 1000 GeV. The observation window covered by MAGIC does not contain the first prominent peak detected at keV energies, where the *Swift* and Konus/*Wind* spectra were taken. The upper limits are compatible with naive extensions of the power-law spectrum up to hundreds of GeV.

For the first time, a Cerenkov telescope is now able to perform direct observations of the prompt emission phase of GRBs. Although strong absorption of the high-energy γ-ray flux by the MRF is expected at high redshifts, given its sensitivity to low fluxes and fast slewing capabilities, the MAGIC Telescope is expected to detect about one GRB per year if GRB spectra extend to the domain of hundreds of GeV.

The construction of the MAGIC Telescope was mainly made possible by the support of the German Bundesministerium für Bildung und Forschung and Max-Planck-Gesellschaft, the Italian Istituto Nazionale de Fisica Nucleare, and the Spanish Comisioń Interministerial de Ciencias y Tecnología, to whom goes our grateful acknowledgement. We are grateful for all the hard work done by the GCN team, especially Scott Barthelmy, and to all the people of the *Swift* Science Center, who kindly provided us with data and the tools to analyze them. In particular, we are indebted to Professor Guido Chincarini, Abe Falcone, and Professor David Burrows from the *Swift* collaboration. We are also grateful to Nicola Omodei for fruitful discussions on the physics of GRBs. We would also 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. This work was further supported by ETH Research Grant TH 34/04 3 and grant 1P03D01028 from the Polish Ministerstwo Nauki i Informatyzacji.

Facilities: MAGIC

REFERENCES

Atkins, R., et al. 2005, ApJ, 630, 996
Band, D., et al. 1993, ApJ, 413, 281
Breiman, L. 2001, Machine Learning, 45, 5
Bretz, T., Dorner, D., & Wagner, R. 2003, Proc. 28th Int. Cosmic Ray Conf. (Tsukuba), 5, 2943
Bretz, T., et al. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), 4, 315
Connaughton, V., et al. 1997, ApJ, 479, 859
de Jager, O. C., & Stecker, F. W. 2002, ApJ, 566, 738
Dermer, C. D., & Atoyan, A. 2004, A&A, 418, L5
Dingus, B. L. 1995, Ap&SS, 231, 187
Falcone, A., et al. 2005, GCN Circ. 3581, http://gcn.gsfc.nasa.gov/gcn/gcn3/3581.gcn3
Fegan, D. J. 1997, J. Phys. G, 23, 1013
Galante, N., Bastieri, D., Gaug, M., Garczarczyk, M., & Peruzzo, L. 2003, Proc. 28th Int. Cosmic Ray Conf. (Tsukuba), 5, 2753
Galante, N., et al. 2005, GCN Circ. 3747, http://gcn.gsfc.nasa.gov/gcn/gcn3/3747.gcn3
Gaug, M., Bartko, H., Cortina, J., Rico, J. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), 5, 375
Götting, N., & Horns, D. G. 2003, GCN Circ. 1007, http://gcn.gsfc.nasa.gov/gcn/gcn3/1007.gcn3
González, M. M., Dingus, B. L., Kaneko, Y., Preece, R. D., Dermer, C. D., & Briggs, M. S. 2003, Nature, 424, 749
Golenetskii, S., Aptekar, R., Mazets, E., Pal'shin, V., Frederiks, D., & Cline, T. 2005, GCN Circ. 3619, http://gcn.gsfc.nasa.gov/gcn/gcn3/3619.gcn3
Goodman, J. 1986, ApJ, 308, L47
Hillas, A. M. 1985, Proc. 19th Int. Cosmic Ray Conf. (La Jolla), 3, 445
Hurley, K., et al. 1994, Nature, 372, 652
Jarvis, A., et al. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), 4, 455
Kneiske, T. M., Bretz, T., Mannheim, K., & Hartmann, D. H. 2004, A&A, 413, 807
Lazzati, D., Rossi, E., Ghisellini, G., & Rees, M. J. 2004, MNRAS, 347, L1
Mészáros, P., & Rees, M. J. 1993, ApJ, 418, L59
Mirzoyan, R. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), 4, 23
Nikishov, A. I. 1961, Zh. Eksp. Teor. Fiz., 41, 549 (English transl. Soviet Phys.–JETP Lett., 14, 392 [1962])
Paczyński, B. 1986, ApJ, 308, L43
Palmer, D., et al. 2005, GCN Circ. 3597, http://gcn.gsfc.nasa.gov/gcn/gcn3/3597.gcn3
Pe'er, A., & Waxman, E. 2004, ApJ, 603, L1
Preece, R. D., Briggs, M. S., Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S., & Band, D. L. 2000, ApJS, 126, 19
Ryde, F. 2004, ApJ, 614, 827
Rolke, W., López, A., & Conrad, J. 2005, Nucl. Instrum. Meth. Phys. Res. A, 551, 493
Stern, B. E., & Poutanen, J. 2004, MNRAS, 352, L35
Vietri, M. 1995, ApJ, 453, 883
Waxman, E. 1995, Phys. Rev. Lett., 75, 386
Zhou, X. 2003, Proc. 28th Int. Cosmic Ray Conf. (Tsukuba), 5, 2757