MAGIC observation of Globular Cluster M13 and its millisecond pulsars

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***Abstract*. Based on MAGIC observations from June and July 2007, we present upper limits to the $E >$ 140 GeV emission from the globular cluster M13. Those limits allow us to constrain the population of millisecond pulsars within M13 and to test models for acceleration of leptons inside their magnetospheres and/or surrounding. We conclude that in M13 either millisecond pulsars are fewer than expected or they accelerate leptons less efficiently than predicted.**

***Keywords*: gamma rays: observations — gamma rays: individual (M13) — gamma rays: globular cluster**

I. Introduction

Globular clusters (GC) are very interesting sites for probing high energy processes due to their large content of evolved objects like millisecond pulsars (MSP). It has been estimated that a typical massive GC contains of the order of 100 MSP [1]. Up to now the largest samples of MSPs discovered are located in the GC Ter 5 (23 MSP), and Tuc 47 (22 MSP) (see e.g. [2]).

TeV γ-rays fluxes from GC have been predicted based on estimates on the population of MSPs and the efficiency of lepton acceleration in their surrounding (see [3] and [4]). The flux level is detectable by the current generation of cherenkov telescopes like MAGIC. The γ-rays would be produced by accelerated leptons scattering off photons of the microwave background radiation or the thermal emission of an extremely dense cluster of solar mass stars inside the GC. Acceleration of leptons could take place either in the shocks produced by the collision of the MSPs winds within the GC, or in the pulsar inner magnetosphere or their wind regions. Furthermore, the inner MSP magnetosphere could be a production site for γ-rays in the sub-TeV energy range as it is predicted from model calculations [5], [6]. Additional contribution to the sub-TeV γ-ray emission could be produced in the vicinity of radio emitting blocked pulsars [7], [8] inside low mass binary systems [9].

No VHE γ-ray emission could be detected so far in any GC. The few experimental results on VHE γ-ray emission reported in the literature are upper limits on the emission of M13 by the *WHIPPLE* Collaboration [10], M15 by the *VERITAS* Collaboration [11], and ω Centauri by the *CANGAROO* Collaboration [12]. Very recently, the *Fermi* LAT telescope has detected high energy γ-ray emission ($E > 100$ MeV) from one of the closest and most massive GC, Tuc 47 [13], and *HESS* has obtained an upper limit of 6.7×10^{-13} ph cm^{-2} s^{-1} for energies $E > 800$ GeV [14], but given the possible complexity of the emission in the GeV range, it is not possible to establish any connection between these results. From the *HESS* result constrains to the magnetic field in the pulsar nebula as a function of the number of MSP in the GC can be drawn for the model in [4]. In addition restrictions to the efficiency of the rotational energy converted by the MSPs into relativistic leptons can be placed for the model described in [3].

Here we report the results of observations with the MAGIC telescope of the globular cluster M13, and present the constraints that our results impose to the population of millisecond pulsars and their lepton acceleration efficiency. M13 belongs to the class of ordinary globular clusters, and its estimated mass is 6×10^5 M$_\odot$. It is located in the northern constellation Hercules at a distance of 7 kpc and thus one of the closer GC. Its core radius is about ~ 1.6 pc, with a half mass radius of $\sim$ 3.05 pc [15]. Up to now 5 millisecond pulsars have been detected in M13, with periods ranging between 2 and 10 ms. The *WHIPPLE* Collaboration derived from their observation a flux upper limit of 1.08×10^{-11} ph. cm^{-2} s^{-1} at energies $E > 500$ GeV [10].

II. Observations and data analysis

The MAGIC telescope is an Imaging Atmospheric Cherenkov Telescope (IACT) located at the Observatory Roque de los Muchachos on the Canarian Island La Palma (28.75°N, 17.86°W, 2225 m a.s.l.). It has an exceptional light detection efficiency provided by the combination of a 17 m diameter mirror and a pixelized camera composed of 576 high quantum efficiency, hemispherical photomultiplier tubes (PMT). The standard trigger threshold of MAGIC is $\sim$ 60 GeV. For energies above 150 GeV, the telescope angular and energy resolutions are $\sim$ 0.1 deg. and $\sim$ 25% respectively (see [16] for further details). In April 2007 the data acquisition system of MAGIC was upgraded with multiplexed 2 GHz Flash Analog-Digital converters which improved the timing resolution of the recorded shower images [17]. Accordingly the sensitivity of MAGIC improved significantly to 1.6% of the Crab Nebula flux above 270 GeV for 50 hours of observation [18].

We observed M13 at zenith angles ranging from 8° to 31° between June 12th and July 18th of 2007 in the false-source tracking (wobble) mode [19]. Two tracking positions 24' offset in RA on opposite sides of M13 were used. This technique allows for a reliable estimation of the background with no need of extra observation time. The collected data amount to 20.7 hours effective observation time after rejecting events affected by unstable hardware or environmental conditions. Besides this, events with a collected charge below 300 photo-electrons were rejected in order to maximize the analysis sensitivity. Due to this selection the analysis threshold is 190 GeV.

The data analysis was carried out using the standard MAGIC analysis and reconstruction software chain, which proceeds in several steps. After the standard calibration of the PMT signal pulses [20], pixels containing no useful information for the shower image reconstruction are discarded by an image cleaning procedure [18]. Then for the events image parameters are calculated [21] using the surviving pixels. In addition to the classical Hillas parameters, two timing parameters are computed, namely: the gradient of the arrival times of the Cherenkov photons along the shower axis; and their arrival time spread over the whole shower. The primary particle identification in each event is achieved using a multidimensional classification procedure based on the Random Forest (RF) method [22]. In the RF the probability to be a hadron induced event, the so called hadronness, is computed for each event based on its image and time parameters. Another RF is trained with a Monte Carlo simulated γ-ray sample to estimate the energy on an event by event basis. Finally the angle between the major axis of the shower image ellipse and the source position in the camera, the so called Alpha angle, is used to select γ-ray candidates in the direction of the source. To estimate the remaining background, the angle Alpha is also computed with respect to the anti source position. The anti source position is 180° rotated to the source position with respect to the camera center.

Main contributions to the systematic uncertainties of our analysis are the uncertainties in the atmospheric transmission, the reflectivity (including stray-light losses) of the mirrors and the light catchers, the photon to photo-electron conversion calibration and the photo-electron collection efficiency in the photomultiplier front-end. A detailed discussion of their contribution to the flux uncertainties can be found in [16], where they are estimated to add up to 30% of the measured flux value.

III. RESULTS

Figure 1 shows the obtained Alpha angle distribution for the source and the background regions. A hadronness cut tuned to yield an energy independent γ-ray selection efficiency of 80%, estimated by means of a Monte Carlo simulation has been applied. We define the signal region as the smaller interval in Alpha angle that contains 80% of the γ-rays for each energy bin, estimated using a Monte Carlo simulation. Their lower bounds are at Alpha$=\ 0$ and the upper ones are shown in second column of Table I for each energy bin. We find -23 ± 57 excess events after background subtraction in the signal region for energies above $E = 140$ GeV. Furthermore, no significant signal is present in a region extending 1 deg of radius around M13. The obtained upper limits to the VHE flux from M13 for different energy bins, are shown in Table I. These have been computed using the Rolke method [23] at a 95% confidence level, and they take into account a 30% systematic uncertainty in the flux level. The upper limit to the integral flux for energies above $E = 200$ GeV, assuming a spectral index of 2.6, is 5.1×10^{-12} cm^{-2} s^{-1}.

TABLE I: Differential upper limits

Energy bin GeV	Upper Alpha cut (deg)	Events	Background events	Excess UL (95% CL)	Flux UL (cm^{-2} s^{-1}TeV^{-1})
140 – 200	8	487	517 ± 23	37	7.2×10^{-11}
200 – 280	10	683	681 ± 27	95	5.1×10^{-11}
280 – 400	8	254	242 ± 16	75	2.2×10^{-11}
400 – 560	6	62	73 ± 9	14	2.4×10^{-12}
560 – 790	4	32	27 ± 5	27	2.7×10^{-12}
790 – 1120	4	4	5.7 ± 2.4	5.8	3.7×10^{-13}

IV. COMPARISON WITH MODELS

In Figure 2 we compare our flux upper limits with the theoretical γ-ray spectra calculated in [3]. In this

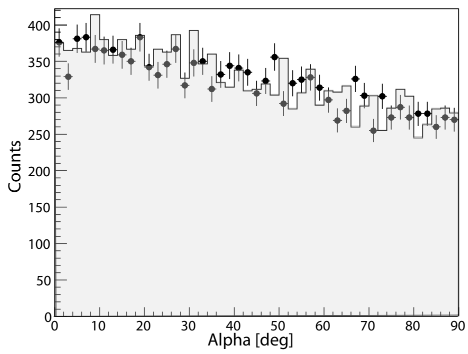

Fig. 1: The Alpha distribution for the selected γ-ray candidates from the signal (black dots) and background (grey shaded) region. No significant signal is present in the data sample.

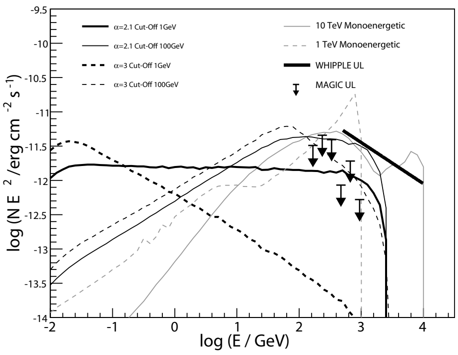

Fig. 2: The MAGIC γ-ray flux upper limits for M13 compared with spectra expected for the range of parameters of the model shown in Figure 9 and 10 of [3]. The specific γ-ray spectra are calculated for lepton upper energy cut-off at 3 TeV and lower energy cut-off at 1 GeV (black thick) and 100 GeV (black thin), and power-law spectral indices of 2.1 (solid) and 3 (dashed). The γ-ray spectra produced by mono-energetic leptons of 10 TeV and 1 TeV are shown by a grey solid curve and a dashed one respectively. All calculations are computed assuming the conservative value of 1 for the free parameter of the model $N_{\rm MSP} \cdot \eta$. The Whipple differential upper limit shown here has been derived from the integral quoted in [10] assuming a spectral index of 2.6.

model, leptons are injected into the GC volume according to a power-law spectrum, upon acceleration in the shocks produced in the collisions of the pulsar winds of several MSPs. The γ-rays are then produced via Inverse Compton scattering of microwave background radiation photons and from thermal radiation arising from the whole GC. Constrains to the total power of all injected leptons ($L_{\rm e}$) can be derived by comparing our upper limits to the theoretical expected values. The theoretical predictions are required to be always lower than our upper limits and the we assume a distance of 7 kpc to M13. The thus derived upper limits to $L_{\rm e}$ are reported in Table II for different assumptions of the spectral shape of the injected leptons, i.e. for different values of the spectral index α between the minimum energy $E_{\rm min}$ and the maximum energy defined by the escape of leptons from the shock. We calculate the upper limits for two energies in the case of mono energetic lepton injection (1 TeV and 10 TeV). Generic parameter values for MSPs (surface magnetic field 10^9 G and rotational period 4 ms) are assumed. This enables us to translate the limits on $L_{\rm e}$ into limits to the product of the number of MSPs in M13 ($N_{\rm MSP}$) times the efficiency of the rotational energy conversion of MSPs into relativistic leptons (η).

TABLE II: Upper limits on the power of injected leptons ($L_{\rm e}$) and in $N_{\rm MSP} \cdot \eta$

$E_{\rm min}$ α	100 GeV 2.1	100 GeV 3.0	1 GeV 2.1	1 GeV 3.0	mono: 1 TeV	mono: 10 TeV
$L_{\rm e}$ ($\times 10^{35}$ erg s^{-1})	0.6	1.0	1.0	60	0.2	0.5
$N_{\rm MSP} \cdot \eta$	0.5	1.0	1.0	50	0.2	0.4

The results are shown in Table II. In example up to 100 MSPs are predicted to be contained in M13 [1]. On the other hand, the efficiency of lepton injection from the inner magnetospheres of millisecond pulsars has been estimated to be $\eta \sim 0.1$ in terms of the extended polar gap model [24]. Hence the product of $N_{\rm MSP} \cdot \eta$, can be most likely of the order of $\sim$ 10. In Table II our upper limits to this product for the various considered model parameters are shown. For most of the considered models $N_{\rm MSP} \cdot \eta$ is significantly below $\sim$ 10. The model with the soft spectrum of leptons which extends down to 1 GeV is the only one we can not strongly constrain. Note that even if the number of MSP in M13 is only equal to 5 (which is the up to now detected number [2]), we can already obtain the acceleration efficiency of leptons to be $\sim$0.1 in the case of their injection with the hard (spectral index 2.1) and mono-energetic spectrum respectively.

V. Conclusions

We present the strongest upper limits to date on the VHE γ-ray flux from the massive globular cluster M13. Our upper limit is $\sim$ 2 times lower than the previous reported limit for VHE energy emission from M13 quoted by *WHIPPLE*, and extends to energies down to 140 GeV. With these upper limits we can constrain the population of the millisecond pulsars expected in M13 and the acceleration scenarios of leptons by millisecond pulsars. Our result strongly suggests that either the number of millisecond pulsars in M13 is significantly lower than the estimate of $\sim$ 100, or the energy conversion efficiency from millisecond pulsars to relativistic leptons is significantly below the value quoted in recent modeling of high energy processes in the magnetospheres of millisecond pulsars.

Acknowledgements

We would like to thank the Instituto de Astrofisica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The support of the German BMBF and MPG, the Italian INFN and Spanish MICINN is gratefully acknowledged. This work was also supported by ETH Research Grant TH 34/043, by the Polish MNiSzW Grant N N203 390834, and by the YIP of the Helmholtz Gemeinschaft.

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