Search for VHE $\gamma$-ray emission from Geminga with the MAGIC telescopes

Simon Bonnefoy$^1$, Marcos López$^1$, Takayuki Saito$^2$ for the MAGIC Collaboration.

$^1$ Universidad Complutense de Madrid, E-28040 Madrid, Spain,  $^2$ Max-Planck-Institut für Physik, D-80805 München, Germany
marcos@gae.ucm.es

Abstract: The recent detection of pulsed emission from the Crab pulsar up to 400 GeV by the MAGIC and VERITAS collaborations showed that pulsar spectra can extend beyond what was previously expected. The origin of this high energy component in the Crab pulsar is not yet clear, but it seems to favour models in which gamma-ray emission takes place further away from the neutron star surface. The detection of such a high energy pulsation in other pulsars will definitely help us to understand the physics involved in the process. With such a goal, the MAGIC collaboration have carried out observations of the Geminga pulsar in winter 2012/13, after the recent upgrade of the telescopes. Here we report about the first results obtained during this observation campaign.

Keywords: pulsars, IACT, MAGIC

1 Introduction

Geminga is the prototype of the radio-quiet pulsar population and the second brightest persistent source in the GeV sky. The period of Geminga ($P \sim 237$ ms) and its derivative ($P \sim 1.1 \times 10^{-14}$ s/s) correspond to a spin-down age of $\tau \sim 340$ kyr, a spin-down power $E_{\text{rot}} = 3.3 \times 10^{34}$ erg s$^{-1}$ and a surface magnetic field $B_{\text{surf}} \sim 1.6 \times 10^{12}$ G. The distance to the source of $\sim 250$ pc (the closest $\gamma$-ray object of this type) makes Geminga, together with Crab and Vela, one of the known pulsars with the highest spin-down flux (defined as $E_{\text{rot}}/d^2$), which potentially should guarantee the highest gamma-ray fluxes. The resulting weak magnetic field at the light cylinder radius ($B_{\text{LC}} \sim 10^3$ G in respect to the Crab case, $B_{\text{LC}} \sim 10^6$ G), seems to provide most favourable conditions for the acceleration of particles in the vicinity of the pulsar.

The Geminga pulsar spectrum published by the Fermi/LAT collaboration after one year of data is described by a power-law with an exponential cutoff, with a cutoff energy of $E_c = (2.46 \pm 0.17)$ GeV [1]. Nevertheless, it is interesting to note that a deviation from the exponential cutoff is seen at the highest energy points in the Geminga spectrum (see Fig. 6 in [1]). A similar analysis by the Fermi/LAT collaboration of the Crab spectrum gave a cutoff energy for Crab of $E_c = (5.8 \pm 1.2)$ GeV. However, recent detection of pulsed emission from the Crab pulsar up to 400 GeV by the MAGIC [2,3] and VERITAS [4] collaborations showed that pulsar spectra can extend beyond what was suggested by these cutoff energies. We had therefore investigated the behaviour of Geminga at VHE energies, by analysing all the Fermi/LAT data available to date (until March 2013). The pulsation is still clearly seen above 20 GeV, with a prominent second peak (P2) surviving at these energies (though the statistics are low). Moreover, we see that there are five photons with energies greater than 50 GeV compatible with emission coming from P2.

Geminga has been also detected as a DC source. A few years ago, an X-ray nebula was discovered around the Geminga pulsar using the XMM-Newton and Chandra satellites [5]. Both detections showed the presence of an extended structure behind the pulsar aligned with its proper motion direction, of $\sim 25''$ long and $\sim 5''$ thick in the case of Chandra. At radio frequencies, many observers have attempted to detect Geminga, both as a continuum and as a pulsating source. Only the deepest VLA interferometric observation of Geminga performed in 2004, resulted in the detection of continuous radio emission. Overall, the Geminga radio tail is compatible with the scenario of a synchrotron-emitting pulsar wind nebula. At Fermi/LAT energies the Geminga nebula is not visible. At TeV energies, Whipple obtained a flux upper limit for DC emission of $8.8 \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ at 0.5 TeV, while HEGRA obtained an upper limit of 13% of the Crab flux below 1.5 TeV [6]. At higher energies, the Milagro collaboration reported the detection of TeV $\gamma$-ray emission from the direction of Geminga at a significance level of 6.3$\sigma$. Milagro observes an emission region that is extended by 2–3 degrees, with a flux at 35 TeV of $37.7 \times 10^{-17}$ TeV$^{-1}$ cm$^{-2}$ s$^{-1}$ [7].

2 The MAGIC telescopes

The two 17 meter diameter MAGIC telescopes constitute a last-generation instrument for Very High Energy (VHE) $\gamma$-ray observations, exploiting the Imaging Air Cherenkov (IACT) technique. The telescopes are located at a height of 2200 m a.s.l. on the Roque de los Muchachos Observatory, in La Palma island (Spain). MAGIC detects the faint flashes of Cherenkov light produced when $\gamma$-rays (or cosmic-rays) plunge into the earth atmosphere and initiate showers of secondary particles. The Cherenkov light emitted by the charged secondary particles is reflected by the mirrors of the telescopes and an image of the shower is obtained in each telescope camera. An offline analysis of the shower images allows the rejection of the hadronic cosmic ray background, the measurement of the direction of the incoming $\gamma$-rays, and the estimation of their energy. The analysis is based on the comparison of image parameters with Monte Carlo simulations.

The MAGIC telescopes were built with the aim of achieving the lowest possible energy threshold. The first MAGIC telescope started observations in 2004, incorporating a number of technological improvements in its design. MAGIC achieved the lowest energy threshold among instruments of its kind, closing the gap between space-borne and ground-based instruments. The introduction of a second telescope in fall 2009, enabled the instrument to perform stereoscopic
observations with significantly better sensitivity and angular resolution. In summer 2011 the readout systems of both telescopes have been upgraded and in summer 2012 the camera of the MAGIC I telescope has been replaced by a more finely pixelized one. The new MAGIC I camera, equipped with 1039 photomultipliers, is a close copy of the one used for the MAGIC II telescope. The upgrade of the camera has also allowed to increase the area of the trigger region in MAGIC I by a factor of 1.7. With respect to single telescope observations, a factor 2 to 3 improvement in significance is achieved. The differential sensitivity at low energies (∼60-100 GeV) is 10.5% of the Crab Nebula flux (C.U.) for 50 h integration. Above 250 GeV, the integral sensitivity is 0.7% C.U. For more details about the current instrument’s performance see [8].

3 Observations and data analysis

Observations of the Geminga pulsar were performed between December 2012 and March 2013, with the upgraded MAGIC telescopes. During this period, a total of ∼75 hours were taken at low zenith angles, to assure the lowest possible energy threshold. All the observations were carried out in the so-called wobble mode, where the source is offset 0.4° from the camera center. After rejection of data taken under unfavourable weather or technical conditions, ∼61 hours of data remained for the analysis. Together with each event image, we recorded the absolute arrival time of each event with a precision of better than 1 µs from a GPS receiver. To check the performance of the MAGIC time acquisition system, we made periodic observations of the Crab pulsar in the optical wavelength with a special photodetector located at the MAGIC-II camera centre [9].

In the analysis, each shower image is cleaned to remove the influence of the night sky background, and parameterized to describe its main features. The image parameters which describe the shape of the image are used to estimate the nature of the incoming particle. This is done by using a Random Forest method, which associates to each event a hadronness parameter representing the probability of the event to be a hadron. The θ parameter, gives the estimated angular distance between the position of the source and the reconstructed position of the source in the camera plane. We apply soft hadron rejection cuts, consisting basically in a cut in hadronness and θ. The cuts are obtained for different energy bins by using a training sample of contemporaneous Crab nebula data.

For the search of pulsed emission, a periodicity analysis was done. The arrival time of each event was first transformed to the barycenter of the solar system using psearch, a dedicated program within the MARS framework [10]. After transformation to the solar barycenter, we calculate for each event the corresponding rotational phase of the Geminga pulsar starting from ephemeris provided by the Fermi/LAT collaboration [11]. The ephemeris were corrected to account for a drift observed when extrapolating the ephemeris to 2012/13 data. The resulting Geminga light curve obtained from the analysis of the data provided by the Fermi/LAT detector above 1 GeV can be seen in Figure 1 (top). Two peaks can be seen, namely P1 (main pulse) and P2 (interpulse), being P1 the one centred at phase 0 in this analysis.

4 Results

The histogram of the phase distribution of the Geminga pulsar obtained by MAGIC is shown in Figure 1 (bottom) for energies above 50 GeV, corresponding to the energy threshold of this analysis. The bin width corresponds to ∼10.8 ms (1/22 of the Geminga rotational period). The shaded areas show the positions of peaks P1 and P2 as seen in the Fermi/LAT light curves.

To test for the presence of a periodic signal in the data, we used three different methods (see inset in Figure 1 (bottom)). The first two are uniformity tests: the H-Test [2] (a periodicity test that is commonly used for periodicity searches) and the well known Pearson’s χ² that tests the null hypothesis that the pulse profile follows a uniform distribution. These tests gave a similar significance. The last method is a single hypothesis test that assumes that γ-ray emission is expected in two phase intervals around the main pulse and inter pulse, respectively. For the selection of the two signal regions we fitted the Geminga light curve obtained with Fermi/LAT to a double asymmetric lorentzian function. Thus we select P1 from 0.95 to 1.06, and P2 from 0.44 to 0.53. The background is estimated from the remaining events in the region 0.65-0.85. In this way we obtain the significances quoted in Table 1.

No significant correlation was found between the pulsar phase distribution of Geminga and the MAGIC data above 50 GeV.

<table>
<thead>
<tr>
<th>Energy range (GeV)</th>
<th>P1</th>
<th>P2</th>
<th>P12</th>
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<tr>
<td>&gt; 50</td>
<td>1.8σ</td>
<td>0.4σ</td>
<td>1.4σ</td>
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Table 1: Significances for pulsed emission coming from P1, P2 and for the total pulsed emission (P1+P2).

5 Conclusions

During winter 2012/13, the Geminga pulsar was observed for 75 hours by the MAGIC telescopes. In the analysis presented here, we have searched for evidence of pulsed and unpulsed emission coming from Geminga at very high energies. We have not found any significant signal above 50 GeV. A refined analysis is under way, which would allow a better overlap with Fermi/LAT data.

6 Acknowledgments

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References

Figure 1: Top: Geminga light curve above 1 GeV obtained in the analysis of the data provided by the Fermi/LAT detector. Two peaks are clearly visible, namely P1 (centred for this analysis at phase 0) and P2. Bottom: Light curve of the Geminga pulsar obtained with MAGIC at energies above 50 GeV. The grey areas show the signal regions where the emission from P1 and P2 is expected, according to the Fermi/LAT light curve. Each light curve is shown over two pulse periods for a better comparison.

    LATPulsarTimingModels/Latest/J0633+1746