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MAGIC detection of Geminga: an Inverse Compton tail?

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We report the detection of pulsed emission from the Geminga pulsar (PSR J0633+1746) with the MAGIC telescopes. After the Crab and Vela pulsars, Geminga is the third pulsar detected in the very-high-energy domain, and its estimated age of 340 ky makes it the oldest one. The spectrum derived by MAGIC extends from 15 GeV to 75 GeV and can be modeled by a power-law function with spectral index $\Gamma = 5.62 \pm 0.54$. Joint fits to MAGIC and Fermi-LAT data disfavour the existence of a sub-exponential cut-off in this energy range. Our results are discussed in the framework of the outer gap pulsar model. The measured power-law emission can be interpreted as the transition from curvature radiation to inverse Compton (IC) scattering of charges accelerated in the northern outer gap. The IC component is expected to continue towards higher energies. These results have been published in Acciari et al. 2020 [1].

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1. Introduction

Since the launch of the Fermi-LAT space telescope the number of known gamma-ray pulsars has increased dramatically. With more than 270 detections, pulsars are now the largest class of GeV sources in our galaxy. The spectrum of most Fermi-LAT pulsars exhibits a sharp cutoff at a few GeVs, making them hard to detect with ground-based Cherenkov telescopes. Actually, apart from Geminga, only the Crab [2] and Vela [3] pulsars have been firmly detected from ground. In the case of Crab, the emission continues up to TeV energies following a power-law function without any evidence of a cut-off [4]. The origin of the high-energy emission in pulsars is still unclear. Therefore, finding more pulsars at high energies is one of the main goals of Cherenkov telescopes.

Similarly to Crab and Vela, Geminga (PSR J0633+1746) is one of the strongest sources in the GeV sky. But unlike them, Geminga is much older and lacks radio emission. The first Geminga spectrum obtained by Fermi-LAT already showed a deviation from an exponential cutoff above 10 GeV [5]. However, subsequent attempts to detect Geminga at higher energies with VERITAS [6] and MAGIC [7] were unsuccessful. This made it clear that further technical developments were needed in order to detect Geminga with Cherenkov telescopes.

2. Observations

The MAGIC telescopes are a set of two 17-meter diameter Cherenkov telescopes located on the Canary Island of La Palma. In recent years we have significantly improved their performance below 100 GeV with the introduction of a novel trigger system, the Sum-Trigger-II, which halves the energy threshold of the telescopes. Technical details on the implementation of the Sum-Trigger-II are discussed in [8].

Observations of the Geminga pulsar with MAGIC were carried out using the Sum-Trigger-II system between 2017 and 2019. A total of 80 h of good quality data were collected. A dedicated analysis pipepline was developed to improve the analysis of low-energy events, in which the calibration and the image cleaning are performed in an iterative procedure. The analysis includes the use of dedicated Monte Carlo simulations of gamma-ray showers to properly account for the effect of the geomagnetic field at tens of GeV.

MAGIC observations were combined with 11 years of Fermi-LAT data. Geminga ephemeris were obtained using Fermi-LAT data [9] and used to phase-fold MAGIC events. The two peaks visible in the Fermi-LAT light curve were fitted to symmetric Gaussian functions to obtain the expected phase signal regions for the MAGIC analysis.

3. Results

The Geminga light curve obtained by MAGIC above 15 GeV is shown in Fig. 1. Emission from the second peak, P2, is detected at a significance level of 6.25 σ. No significant signal is found in MAGIC data in the P1 phase region. The MAGIC spectrum in the energy range $15 - 75$ GeV is well-represented by a power-law function with spectral index $\Gamma = 5.62 \pm 0.54$ [1]. The spectrum merges smoothly with the one measured by Fermi-LAT and is in agreement with the upper limits previously reported by MAGIC [7].

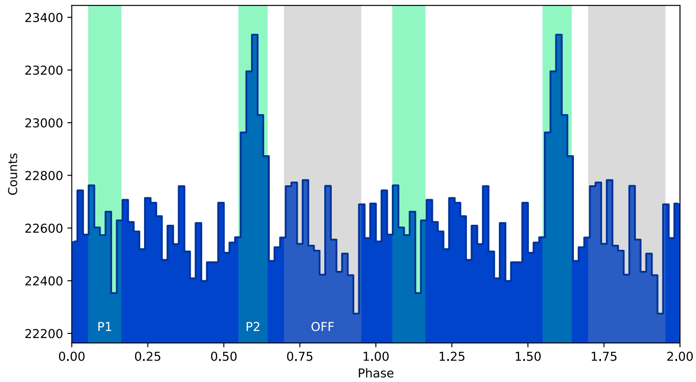

Figure 1: Geminga light curve measured by MAGIC above 15 GeV. Two rotation cycles are shown for clarity. The green-shaded regions highlight the phase intervals corresponding to the P1 and P2 peaks.

To test for the presence of an exponential cut-off in the combined MAGIC and Fermi-LAT spectrum, expected in classical pulsar models, we performed a joint fit to a power-law function with an exponential cut-off. A pure exponential cut-off is rejected at a significance level of 18 σ. Also, the sub-exponential cut-off case is disfavoured at 3.6 σ.

We compared our observational results with simulations of the Geminga pulsar in the framework of the outer gap model [10]. The measured emission from P2 by MAGIC requires the angle between the observer's line of sight and the pulsar rotation axis to be nearly 90°. In this case, the detected gamma rays would be produced in the northern outer gap via curvature radiation, for photons below $\sim$ 40 GeV, and by Inverse Compton scattering for the higher end of the reported spectrum.

4. Conclusions

We have presented the detection of pulsed gamma-ray emission from the Geminga pulsar with the MAGIC telescopes. Data were taken using the Sum-Trigger-II system developed for reducing the energy threshold of the telescopes. The emission detected above 15 GeV coincides in phase with the position of the second emission peak of the pulsar. The measured spectrum up to 75 GeV merges smoothly with the one measured at lower energies by Fermi-LAT, and is well described by a power law with spectral index $\Gamma = 5.62 \pm 0.54$. Simulations of the outer gap pulsar model indicate that electrons accelerated in northern outer gap would be responsible for the most energetic gamma rays detected in the Geminga pulsar.

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References

[1] V. A. Acciari *et al.* (MAGIC Coll.), "Detection of the Geminga pulsar with MAGIC hints at a power-law tail emission beyond 15 GeV," Astron. Astrophys. **643** (2020) L14 doi:10.1051/0004-6361/202039131 [arXiv:2011.10412 [astro-ph.HE]].

[2] E. Aliu, et al. (MAGIC Coll.), *Science* **322** (2016) 1221

[3] H. Abdalla et al. (H.E.S.S. Coll.), *Astronomy & Astrophysic* **620** (2018) A66

[4] S. Ansoldi et al. (MAGIC Coll.), *Astronomy & Astrophysics* **585** (2016) A133

[5] A. Abdo (Fermi-LAT Coll.) *Astrop. Journal* **720** (2010) 272

[6] E. Aliu. et al. (VERITAS Coll.), *Astrop. Journal* **800** (2015) 61

[7] M. L. Ahnen et al. (MAGIC Coll.), *Astronomy & Astrophysics* **591** (2016) A138

[8] F. Dazzi *et al.*, *IEEE Transactions on Nuclear Science* **68** (2021) 7 doi:10.1109/TNS.2021.3079262

[9] M. Kerr, P. S. Ray, S. Johnston, R. M. Shannon & F. Camilo, *Astrop. Journal* **814** (2015) 128

[10] K. Hirotani *Astrop. Journal* **766** (2013) 98

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