The Crab pulsar as seen by the MAGIC telescopes

Outline
- The MAGIC telescopes
- Mono observations
- Stereo observations
Collaboration: ~ 150 Physicists, 21 Institutes, 8 Countries:

La Palma, IAC
28° North, 18° West

~2240 m asl

MAGIC in La Palma, Canary Islands, Spain

MAGIC-II in operation since 2009

Goal: Achieve the lowest energy threshold among CTs

Close gap between space & ground-based gamma-ray telescopes
The Cherenkov technique

Basic fact: Gamma-rays absorbed in atmosphere

Satellites
- Direct detection
- Small background
- Small Effective Area $\sim 1\text{m}^2$

Ground Detectors
- Indirect detection
- Enormous hadronic background
- Huge Effective Area $\sim 10^5\text{m}^2$

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MAGIC Physics Targets

 Galactic

 Pulsars/ PWN
 SNRs

 Extragalactic

 AGN
 Radio galaxy

 Fundamental
 Physics

 dark matter
 space time

 Pulsars one of the hottest topics

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Different models try to explain observed γ-ray emission.

- Assume different emitting region in magnetosphere → different emission geometry: PC, OG, SG

Spectrum depends on the physics of the emitting region

Light curves depend on geometry
Gamma-ray pulsars with space telescopes

- 101 pulsars found by Fermi
- Spectra up to $\sim 10$ GeV consistent with exp. cutoff

- Polar Cap rejected
- Outer Gap favored

D. Smith 2011 Fermi Symposium
Are Pulsars visible in VHE \( \gamma \)-rays?

- Models for HE emission (polar cap, outer or slot gap) predict \text{exp. or super exp. cutoffs @ few GeV.}
- Observational challenge for CTs since 20 years
MAGIC tried from the very beginning to detect pulsars
  – Developed dedicated hardware to help to the pulsar program (central pixel, sumtrigger,…)

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<tbody>
<tr>
<td><strong>Telescopes</strong></td>
<td>MAGIC I</td>
<td>MAGIC I</td>
<td>MAGIC I &amp; II</td>
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<tr>
<td><strong>Energy threshold</strong></td>
<td>60 GeV</td>
<td>25 GeV</td>
<td>50 GeV</td>
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<tr>
<td><strong>Sensitivity &gt; 100 GeV</strong></td>
<td>7.5% Crab</td>
<td>4.4% Crab</td>
<td>1.6 % Crab</td>
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<tr>
<td></td>
<td>Insufficient</td>
<td>The lowest</td>
<td>The best g/h</td>
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<tr>
<td></td>
<td>sensitivity</td>
<td>threshold</td>
<td>separation</td>
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MAGIC Crab pulsar Timeline

- **Oct. – Dec. 2005**
  - std. trigger (>60 GeV)
  - 2.9 $\sigma$ excess in $P_2$!

- **Oct. 2007 – Feb 2008**
  - sum trigger (> 25 GeV)
  - 6.4 $\sigma$ excess in $P_1+P_2$!!

  - sum trigger (> 25 GeV)

- **Oct. 2009 – Feb 2011**
  - stereo trigger (> 50 GeV)

**Detection**

**Hint**

(Fermi launched, 2008)

(MAGIC II commissioned, 2008)

(Sum trig. developed, 2008)


(Science 322, 2008)

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First Crab pulsar detection above 25 GeV

Mono Observations with sumtrigger
- Oct.07 to Feb.08: 22.3 h

Clear detection: $6.4\sigma$
Pulses in phase with EGRET

$P1$ clearly visible at 25 GeV
→ First Surprise

Pulsed emission still visible > 60 GeV!
$P2$ became dominant

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Science 322 (2008) 1221

- 59 hours from Oct. 2007 to Feb. 2009 with SumTrigger

\[
P_1 (-0.06-0.04): 6200 +\ 1400 \text{ events (4.3 } \sigma) \\
P_2 (0.32-0.43): 11300 +\ 1500 \text{ events (7.4 } \sigma) \\
P_1 + P_2: 17500 +\ 2300 \text{ (7.5 } \sigma) \
\]

- Obtained total pulsed spectrum and spectra for each peak separately up to 100 GeV

**Inconsistent with the extrapolation of the exponential cutoff (>5 σ).**
**Spectra between 25 GeV and 100 GeV show a power law.**

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<thead>
<tr>
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<th>P₁ + P₂</th>
<th>P₁</th>
<th>P₂</th>
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<tbody>
<tr>
<td>F₀ at 30 GeV [10⁻⁹ cm⁻² s⁻¹ TeV⁻¹]</td>
<td>3.1+-1.0+-0.3</td>
<td>4.5+-2.3+-2.6</td>
<td>10.0 +-1.9 +- 2.6</td>
</tr>
<tr>
<td>Index</td>
<td>-3.4+-0.5+-0.3</td>
<td>-3.1 +- 1.0 +- 0.3</td>
<td>-3.4 +- 0.5 +- 0.3</td>
</tr>
</tbody>
</table>
MAGIC stereo

Two 17m telescopes observing in stereoscopic mode since fall ‘09

Why stereo?

Stereoscopic provides: better reconstruction of shower direction & additional shower parameters

This means:
- Better hadron rejection
- Better angular resolution: 0.1°@100 GeV, down to 0.04° E>1 TeV
- Better energy resolution: 20%@100 GeV, down to 15% at 1 TeV
- Enhances the sensitivity over the whole energy range (2-3 better)
- Energy threshold: ~ 50 GeV

Most sensitive observatory in the range 50-200 GeV
Stereo observations (2009-2011): Detection

- Used 73 h of stereo data from Oct09 to Feb1
  - 43 Wobble, 30 ON/OFF

- H-test gives 6.4 $\sigma$
  - $P_1$: 356 +/- 69 events (5.2 $\sigma$)
  - $P_2$: 880 +/- 101 events (8.9 $\sigma$)

- Pulsed emission detected up to 400 GeV !!

[Image of graph depicting event counts across different energy levels and phases]
Stereo observations (2009-2011): Detection

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P1: 356 +/− 69 events (5.2 $\sigma$)
P2: 880 +/− 101 events (8.9 $\sigma$)

Pulsed emission detected up to 400 GeV !!
Stereo observations (2009-2011): Detection

Light curve morphology

- Peaks width get narrower with energy

The pulses are aligned, becoming very narrow @ VHE
VHE spectrum of Crab pulsar

- **MAGIC Stereo** provides spectra up to **400 GeV**.

- **Mono/stereo spectra** agree... and go well beyond a cutoff at few GeV!

In agreement with VERITAS (Aliu et.al 2011)
Stereo observations (2009-2011): Spectrum

First pulsar Phase-resolved spectrum @ hundreds GeV!

- **First Peak**
  - Good agreement to MAGIC-Mono (< 2 Sigma despite different systematics)

- **Second Peak**

**SUMMARY**

MAGIC measurements rule out extrapolation of Fermi exponential fit.
A possible explanation for a VHE tail (I)

- Extension of Outer Gap scenario by K. Hirotani (arXiv:1108.5391)
  - Detected VHE pulsed emission caused by IC scattering of secondary & tertiary e±-pairs on magnetospheric IR-UV ph.
  - Predicted Power law component from 10 Gev up to 1 TeV
  - In the calculations, angle between rotational and B axes assumed to be 65°, and observer’s viewing angle 106°.

**MAGIC mono & stereo spectra reproducible with self-consistent OG model**
A possible explanation for a VHE tail (II)

Alternative explanation by Aharonian et al. (*Nature* 482, 2012)

- VHE component resulting from the abrupt acceleration of a cold ultrarelativistic wind
  - Wind accelerated in a narrow zone (20-50 light-cylinder radii), up to a Lorentz factor of \((0.5 - 1.0) \cdot 10^6\)
  - IC γ-ray emission of the wind explains emission >100 GeV
Summary

In the last years MAGIC contributed to the understanding of the gamma-ray emission of the Crab Pulsar

MAGIC detected the Crab pulsar in mono and stereo mode, and with different trigger schemes
- First detection of Crab pulsar with a CT
- Both peaks visible & Cutoff higher than expected

The combination of mono and stereo observations allowed to obtain spectrum from 25 to 400 GeV
- First time phase resolved spectroscopy at VHE
- Spectra following a power law instead of exp. cutoff

Does other pulsar have a power-law tail?