Recent MAGIC Results

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- Introduction
  • MAGIC Stereo system

- Recent Results
  • Extragalactic
  • Galactic

- Summary
The MAGIC Telescopes

- A system of two Cherenkov telescopes, 17 m diameter
- Located at the European Northern Observatory, Instituto Astrofísica de Canarias. La Palma, Spain
- 150 physicists in 21 Institutes
- MAGIC-I in operation since fall 2004
- MAGIC-II in operation since 2009. Commissioning finished
- Lowest energy threshold among IACTs
Low Energy VHE $\gamma$-ray Astronomy

- Interesting to look at low energies
  - Measure soft spectra, cut-offs
  - Objects with higher redshift, not visible at higher energies
  - Overlap with other instruments (FERMI)
  - Less explored region
  - More sources
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<table>
<thead>
<tr>
<th>Source</th>
<th>Redshift</th>
<th>Type</th>
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<td>1ES 1011+496</td>
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<td>FR-I</td>
<td>MAGIC</td>
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<tr>
<td>1ES 0414+009</td>
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<td>HESS</td>
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<td>MAGIC</td>
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<td>VERITAS</td>
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<tr>
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<td>FSRQ</td>
<td>HESS</td>
</tr>
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<td>PKS 1222+21</td>
<td>0.43</td>
<td>FSRQ</td>
<td>MAGIC</td>
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<tr>
<td>3C 66A</td>
<td>0.44 (?)</td>
<td>IBL</td>
<td>VERITAS</td>
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<td>3C 279</td>
<td>0.54</td>
<td>FSRQ</td>
<td>MAGIC</td>
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Low Energy VHE γ-ray Astronomy

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MAGIC-1 vs MAGIC Stereo

- Energy threshold:
  - Analysis threshold $\geq 60$ GeV
- Sensitivity: 1.6% Crab in 50 h
- Angular resolution: $0.1^\circ \ (\sigma \ 2D)$
- Energy resolution: $\sim 25\%$
- Fast repositioning (<20 sec!)
MAGIC-1 vs MAGIC Stereo

- Energy threshold:
  - Analysis threshold $\gtrsim 60$ GeV
  - Sensitivity: 1.6% Crab in 50 h
  - Angular resolution: $0.1^\circ$ ($\sigma$ 2D)
  - Energy resolution: $\sim 25$
  - Fast repositioning (<20 sec!)

- Energy threshold:
  - 50 GeV analysis threshold
  - Sensitivity: <1.0% Crab in 50 h
  - Angular resolution: $0.07^\circ$ ($\sigma$ 2D)
  - Energy resolution: $\sim 15$
  - Fast repositioning (<20 sec!)
Stereo Performances

- Angular resolution
  - Improved from 0.1° in MAGIC-1 to 0.07° at E>300 GeV ($\sigma$ of 2D gaussian, 39% containment)
  - 0.1° at 100 GeV

- Energy resolution
  - Improved from 25% in MAGIC-1 to 15% at E>300 GeV

- Improved background rejection
  - Shower height maximum
Sensitivity improved from 1.6% Crab in MAGIC-1 to <1% (5σ in 50 h). Background reduced to ~1/3
Crab Nebula spectrum

Crab Nebula Spectrum MAGIC Stereo
November 13-15th 2009, 190min effective observation time

Preliminary

No. of gammas / (cm$^2$ s TeV)

$E$ [GeV]

- current fit: curved power law
- HEGRA
Crab Nebula SED


Crab Nebula SED

PRELIMINARY

Energy [MeV]

$E^2 F$ [erg cm$^{-2}$ s$^{-1}$]
Crab Nebula SED

- Overlap with FERMI in the range 50-300 GeV
- Smaller statistical errors!
Recent Results
Extragalactic targets

- **Dark matter**
- **Radio galaxy**
- **GRBs**

**INTRODUCTION**

**EXTRAGALACTIC**

**GALACTIC**

**SUMMARY**

- **AGN**
- **Fundamental Physics**
Extragalactic results

- 17 sources detected, 10 discoveries
  - 3C 279, highest redshift source detected by IACTs
- 3 New sources with the stereo system (Astronomer’s Telegrams 2010):
  - Mar 25: IC 310
  - Jun 19: 4C +21.35 (PKS1222)
  - Jul 22: MAGIC J2001+435
**4C +2135**
- Outburst from FSRQ 4C +2135, $z=0.432$
- Stereo observation under low Moon
- $> 8\sigma$ in 0.5 hours on June 17th 2010
- Flux level $\sim 30\%$ Crab above 100 GeV
- ATEL #2684

**1FGL J2001.1+435**
- Recently identified as a BL Lac object, $z$ unknown
- Stereo observation on 17th July resulted in a discovery with $\sim 7\sigma$ in $\sim 1.5$ hours
- Flux level $\sim 20\%$ Crab above 100 GeV
- Indications of variability in MAGIC and Swift data
- ATEL #2753
Bright Blazars monitoring

- Regular observations of bright TeV Blazars: Mkn 501, Mkn 421, 1ES 1959+650, 1ES 2344+514
- MW-campaigns, ToO, ...
Multiwavelength campaign Jan-Feb 2008 (VERITAS, HESS, MAGIC and Radio, X-ray)

Triggered by MAGIC detection on 1st February flare (9.9σ; 8.0σ single night)

Fast variability. TeV correlated with radio and X-ray emission from core

New MAGIC ATel in February 2010 (#2431)

Radio galaxy with super massive black hole \( \sim 6 \times 10^9 \, M_\odot \) at \( \sim 16 \, \text{Mpc} \)

Followed by increase of radio flare close BH

Science, 325 (2009) 444
3rd MAGIC discovery after optical ToO (Mrk180 and 1ES1011)

Optical light curve: KVA telescope, La Palma

- MAGIC discovery 23rd - 25th April. ATel on 29th April
- On 28th Swift reports high flux (0.3-10 keV)
- MAGIC flux above 400 GeV ≈ 25% Crab. Photon index $\Gamma=3.45\pm0.54$
- 3rd low peaked Blazar after BL Lac and W Comae. Host galaxy detected $z=0.31\pm0.08$
- Flat Spectrum Radio Quasar at z=0.536
- Brightest EGRET AGN (Wehrle+97,98)
- Gamma-ray flares in 1991 and 1996:
  - High dynamical range in EGRET data
  - Rapid variability: \( \Delta T \sim 6\)hr in 1996 flare
- MAGIC observations:
  2006 January–April during

![Graph](MAGIC COLL., SCIENCE 320 (2008) 1752)

- Integral flux (100-500 GeV) [cm\(^{-2}\) s\(^{-1}\)]

- 22 Feb 2006: 2.2\(\sigma\)
- 23 Feb 2006: 6.2\(\sigma\)

- Flux incompatible with const.: 5.04\(\sigma\)
Flat Spectrum Radio Quasar at $z=0.536$

Brightest EGRET AGN (Wehrle+97,98)

Gamma-ray flares in 1991 and 1996:

- High dynamical range in EGRET data
- Rapid variability: $\Delta T \sim 6$ hr in 1996 flare

MAGIC observations:
- 2006 January–April

**Reduction and Analysis**

```
Energy, $E$ [GeV]
70 80 100 200 300 400 500

Differential flux, $dN/dE$ [TeV$^{-1}$ cm$^{-2}$ s$^{-1}$]
$10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$

Integral flux (100-500 GeV) [cm$^{-2}$ s$^{-1}$]
0.6 0.5 0.4 0.3 0.2 0.1 0.0

22 Feb 2006
23 Feb 2006

Flux incompatible with const.: 5.04 $\sigma$
```

**Fit to Measured Spectrum**

$$dN/dE = N_0 \left( \frac{E}{200\text{GeV}} \right)^{-\alpha}$$

$$N_0 = (5.2 \pm 1.7) \times 10^{10} \text{ [TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}]$$

$$\alpha = 4.11 \pm 0.68$$

**Plot**

- **3C279**, measured
- Systematic error band
- EBL-corrected, Primack, $\alpha^* = 2.94 \pm 0.91$
- EBL-corrected, Stecker (fast), $\alpha^* = 0.49 \pm 0.14$

EXCLUDED

STILL ALLOWED

**3C279**

- **Steffen et al., 2006, (fast evolution)**
- **max-EBL (this work)**
- **Primack et al., 2005**
- **Cosmic Microwave Background**
- **Mazin & Raue, upper limit 2007**
- **HESS upper limit, 2006**

EXCLUDED

**3C279**
Follow up observations of 3C279

- MAGIC observations in January 2007
- Only observations at the 16th (~150 min) show significant signal above 150 GeV
- No significant emission during the other 8 observation nights

Hard spectrum confirmed
Photon index consistent with 2006 observations within errors
Perseus Cluster

- At a distance of 77.7 Mpc (z=0.018)
- Brightest X-ray cluster
- Luminous radio mini-halo ~200 kpc
- Central radio galaxy NGC 1275 emitter of γ-rays E>100 MeV
- MAGIC observed 33 h during Nov-Dec 2008
- MAGIC did not see γ-ray emission.

Constraints on emission:
- from Cosmic Rays
- through Dark Matter annihilation
- from NGC1275

- Head-tail radio galaxy. Detection (ATEL #2510) triggered by FERMI data

- Flux above 300 GeV ~2.5% Crab

- Favoured scenario with VHE $\gamma$-rays coming from the inner jet close to the central engine

- Flat spectrum spreads over more than 3 orders of magnitude

J. Aleksic et al., in astro-ph
Galactic targets

- Pulsars
- Quasars
- Galactic center
- Pulsar wind nebulae
- Globular clusters
- Binary pulsars
- SNRs
Detection of 10 objects. 3 are MAGIC discoveries (+1 evidence):

- Crab Pulsar
- LSI 61+303
- IC 443
- Cyg X-1 (4.1σ)

More objects studied. Upper limits on PWNs, SNRs, WR stars, Globular clusters, microquasars, etc.
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Crab Pulsar

- With dedicated low threshold trigger (*Sum trigger*)
- If superexponential cutoff assumed, lower limit on the distance of the emitting region: $6.2 \pm 0.2_{\text{stat}} \pm 0.4_{\text{syst}}$ NS radii

Aliu et al., Science 322 (2008) 1221
**Crab Pulsar**

- With dedicated low threshold trigger (*Sum trigger*)
- If superexponential cutoff assumed, lower limit on the distance of the emitting region: $6.2 \pm 0.2_{\text{stat}} \pm 0.4_{\text{syst}}$ NS radii
- FERMI measured cutoff $5.8 \pm 0.5 \pm 1.5$ GeV. Compatible with MAGIC if EGRET data added to the fit
- FERMI Minimum emission height $> 3.4$ NS radii

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**Energy [MeV]**

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>$10^{11}$</th>
<th>$10^{12}$</th>
<th>$10^{13}$</th>
<th>$10^{14}$</th>
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</thead>
<tbody>
<tr>
<td>$F_{\text{EGRET}}$</td>
<td>Green stars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{\text{Fermi}}$</td>
<td>Red points</td>
<td></td>
<td></td>
<td></td>
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**$E^2 F$ [erg cm$^{-2}$ s$^{-1}$]**

- **FERMI** measured cutoff $5.8 \pm 0.5 \pm 1.5$ GeV. Compatible with MAGIC if EGRET data added to the fit
- FERMI Minimum emission height $> 3.4$ NS radii

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**SUMMARY**
Crab Pulsar

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- FERMI Minimum emission height $> 3.4$ NS radii
- Follow up observations
  - 7.5 sigma above 25 GeV
  - Working on a spectrum
High mass X-ray binary system

Discovered by MAGIC in VHE γ-rays 2005-2006. Highest emission phase 0.6-0.7

LS I +31 606 VHE emission is periodic. P = (26.8 ± 0.2) days

Compatible with the orbital periodicity found in other wavelengths

Multiwavelength campaign October-November 2006

No gamma-radio correlation. Possible X-ray - gamma correlation
- Multiwavelength campaign during September 2007 with MAGIC (54 hours), XMM-Newton (104 ks) & Swift/XRT (29 ks)

- Evidence for correlation with $r = 0.81$ (pfap $\sim 5 \times 10^{-3}$). Averaged flux in orbital phasebin 0.6 - 0.7: $E_{F_{\text{X-rays}}} \sim 2 \times E_{F_{\text{VHE}}}$
Cyg X-3

- X-ray binary system
- MAGIC upper limits over 5 years for different periods and phases

Summary
Summary

- MAGIC stereo observations started in Summer 2009. Today it is the default observation mode
  - Improved performances: higher energy and angular resolution, improved sensitivity (<1% Crab, 50 h) and lower energy threshold
- Complete Physics program will benefit from improvements
  - Lowest energy threshold among the IACTs
  - Unique IACT with a good overlap with FERMI
- First stereo results:
  - Crab Nebula
  - 3 new extragalactic sources
- Upgrade of MAGIC-1 camera in summer 2011
Extragalactic Sources

- M87 (0.0041)
- Mrk 421 (0.031)
- Mrk 501 (0.034)
- Mrk 180 (0.045)
- Mrk 180 (3c66 A/B)
- Mrk 180 (3c66 A/B)
- 1es2344 (0.044)
- 1es1959 (0.047)
- BL Lac (0.069)
- PKS 2155 (0.116)
- 1es1218 (0.18)
- PG1553 (>0.25)
- 1ES 1011 (0.212)
- S5 0716+714 (0.31)
- 3c279 (>0.536)
Galactic Sources

- 4 New galactic sources, 6 more observed

- Crab Nebula
- Crab Pulsar
- Galactic Center
- HESS J1813
- HESS J1834

- LSI 61+303
- IC 443
- Cygnus X-1 (4.1σ)
- TeV 2032
- Cas A
3C 66A/B: just separated by 6’ in the sky

- 3C 66B large FR-I radio galaxy, similar to M87, z=0.0215
- 3C 66A blazar with uncertain redshift, z=0.444 single emission line, host: z=0.321

Sept 2008: Clear VERITAS detection above 100 GeV @ 10% Crab (Swordy 08, ATel 1753)

Shortly after: Fermi GRT reports high state > 20 MeV (Tosti 08, ATel 1759)

Optical outburst in August 2007 triggered MAGIC observations, 54.2 h up to December 2007

Significance of MAGIC detection: 6.0 $\sigma$ (5.4 $\sigma$ after trials)

CoG from 2-dim Gaussian fit: MAGIC J0223+430
- 6.1’ away from 3C66A
- 1.1’ away from 3C66B
- 3C66A excluded 95% (85.4% including 2’ systematics)

Hard spectrum extending up to 2 TeV
Microquasars

- X-ray binaries (stellar Mass BH/NS + Companion Star) showing relativistic jets and accretion disc
- Microquasars have been observed with MAGIC since the first observation cycle
- Different trigger criteria have been followed:
  - Radio bursts
  - X-ray low/hard state
  - Monitoring
  - Super-orbital motion
  - Alarms by Agile

Different trigger criteria have been followed:

Cyg X-1

Albert et al. 2007
Microquasar observations

**GRS 1915 +105**
- 16 nights
- UL: 0.71% Crab
- Flux UL (>250 GeV) [10^{-12} cm^{-2} s^{-1}]
  - T: 0.4[h] T: 0.5[h]
  - σ: -0.9 σ: 1.0

**Cygnus X-1**
- 28 nights
- UL: 1.2% Crab
- Flux UL (>250 GeV) [10^{-12} cm^{-2} s^{-1}]
  - T: 0.5[h]
  - σ: 0.5

**GRS 1915 +105**
- 21 nights
- UL: 0.6% Crab
- Flux UL (>250 GeV) [10^{-12} cm^{-2} s^{-1}]
  - T: 1.8[h] T: 3.2[h]
  - σ: -0.6 σ: -0.3

**Cygnus X-3**
- UL: 0.75 Crab
- Flux UL (>250 GeV) [10^{-12} cm^{-2} s^{-1}]
  - T: 2.0[h]
  - σ: -1.0

UL: 95% c.l.
- Evidence (4.1σ post-trial significance discovered by MAGIC on 24-09-2006)
- Soft spectrum ($\alpha = -3.2$) between ~100 GeV and 1 TeV, with no break
- Extension below MAGIC angular resolution (~0.1°)
- X-ray flare seen by Swift/BAT, RXTE/ASM and Integral. Shift between TeV and X-ray peak

**Cygnus X-1**

**ALBERT ET AL. 2007 APJ 665, L51
• $\gamma$-ray binary discovered by MAGIC (E > 300 GeV) in 2005/2006
• Compact object unknown. B0Ve star as optical companion
• Highly eccentric orbit $e = 0.54$ (Argona et al. 2009)
• Periodic emission with Period 26.496 d in O, R & X-ray
• VHE emission strongly variable