MAGIC observations of blazars

Gamma-ray blazar workshop at SLAC on March 12, 2015

Masaaki Hayashida
(Institute Cosmic-Ray Research, the University of Tokyo)
for the MAGIC collaboration
Outline

1. Status of the MAGIC telescopes
2. Observational results of FSRQs
   1. 3C 279
   2. PKS1510-089
3. Very fast variability in a sub-horizon scale
   1. IC310
4. Recent Atel by MAGIC
   1. S3 0218+357 (z=0.944)

(some other sources like Mkn421, Mkn501 will be included in the David’s talk)
the MAGIC Telescopes

Canary Island of La Palma
the MAGIC Telescopes

Canary Island of La Palma

Observatorio del Roque de los Muchachos
The MAGIC Collaboration

~170 Collaborating Astro-Physicists from 10 Countries

**Bulgaria** Sofia

**Croatia** Consortium (Zagreb, +...)

**Finland** Consortium (Tuorla, +...)

**Germany** DESY Zeuthen, TU Dortmund, MPI Munich, U. Würzburg

**Japan** Consortium (Kyoto, +...)

**Italy** INFN & U. Padova, INFN Pisa & U. Siena, INFN Como/Milano Bicocca, INFN Udine/Trieste & U. Udine, INAF (Consortium: Rome, +...)

**Poland** Lodz


**Switzerland** ETH Zurich

**India** Saha Inst. of Nuclear Physics, Kolkata
current status of the telescope system

- system of two IACTs
- 17 m mirror dishes
- cameras: 1039 PMTs each
- fast read-out system (2 GHz sampling rate)
- fast re-positioning: ~25 s for 180° rotation in azimuth

- energy range: 50 GeV to 30 TeV
- sensitivity above 220 GeV: (0.66 ± 0.03)% of C.U.
- energy resolution: 16% at moderate energies
- angular resolution: < 0.07° above 250 GeV
Current telescope performances

After telescope upgrades (in 2011 and 2012)

• readout board (both telescopes)
• new camera (the first telescope)

Improved by 5-10% at lowest energies (< 100 GeV): performance improved drastically
What MAGIC can see from blazars?
where does \(\gamma\)-ray emission arise in relativistic jets?

\(\gamma\)-ray emission zone

- Dusty torus
- BH accretion disk
- Broad emission line region (BEL)
- UV photon
- IR photon

\(\gamma\) e + e - \(\rightarrow\) \(\gamma\)

Near side? (\(10^{15} \text{--} 17 \text{ cm}\))

or

Far side? (\(10^{18} \text{--} 19 \text{ cm}\))

Masaaki Hayashida (ICRR)
the case of PKS 1222+21

- PKS 1222+21 (z = 0.432), 2nd TeV FSRQ
- One night detection (June 17th 2010) by MAGIC


Good conjunction between Fermi and MAGIC spectra
- should be outside of BLR

not compatible in the simple (canonical) jet model!!
FSRQ 3C 279 (z=0.536)

MAGIC detection (>100 GeV)
in 2006 (MAGIC collab, 2008, Science)

short time (~day) flare


<bent jet model: Far side>

Fermi+MWL in 2008-2010

20 day change of polarization with a γ-ray flare
• 2011 February – June (3 day bin for LAT)
• 1st half: low state
• 2nd half: high state
• highest flux in $\gamma$-ray: $1.3 \times 10^{-6}$ ph cm$^{-2}$s$^{-1}$ at MJD 55668 (half of the highest in 2008-2010)

MAGIC observations
• A: Feb.8 – Apr.12 (low state)
• B: Jun.1 – Jun.8 (high state)
**Fermi-LAT**

<table>
<thead>
<tr>
<th>Period</th>
<th>MJD</th>
<th>fitting model</th>
<th>$\Gamma/\alpha$</th>
<th>$\beta$</th>
<th>$T S$</th>
<th>$-2\Delta L$</th>
<th>Flux ($&gt;100$ MeV) [10^{-7} ph cm^{-2} s^{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Feb 8 – 2011 Apr 12</td>
<td>(55600 – 55663)</td>
<td>PL</td>
<td>2.37 ± 0.06</td>
<td>0.12 ± 0.06</td>
<td>696</td>
<td>6.0</td>
<td>3.5 ± 0.3</td>
</tr>
<tr>
<td>2011 Jun 1 – 2011 Jun 8</td>
<td>(55713 – 55720)</td>
<td>LogP</td>
<td>2.18 ± 0.10</td>
<td>0.12 ± 0.08</td>
<td>701</td>
<td>6.0</td>
<td>3.2 ± 0.3</td>
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<tr>
<td>2011 Jun 1 – 2011 Jun 8</td>
<td>(55713 – 55720)</td>
<td>PL</td>
<td>2.17 ± 0.08</td>
<td>0.07 ± 0.06</td>
<td>401</td>
<td>1.4</td>
<td>8.3 ± 1.0</td>
</tr>
<tr>
<td>2011 Jun 1 – 2011 Jun 8</td>
<td>(55713 – 55720)</td>
<td>LogP</td>
<td>2.02 ± 0.15</td>
<td>0.07 ± 0.06</td>
<td>402</td>
<td>1.4</td>
<td>7.7 ± 1.0</td>
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</tbody>
</table>

**MAGIC (no detection)**

<table>
<thead>
<tr>
<th>Observation period</th>
<th>Observation time [h]</th>
<th>Excess events [counts]</th>
<th>Background events [counts]</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>February - April</td>
<td>11.6</td>
<td>34 ± 82</td>
<td>3354 ± 58</td>
</tr>
<tr>
<td>B</td>
<td>June</td>
<td>6.2</td>
<td>46 ± 60</td>
<td>1790 ± 42</td>
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</tbody>
</table>
Period B: jet structure

- EVPA gradually changing ~ 10 days: optical emission: 3 pc (far side)
- different behaviors between optical (large flare), and X-ray, γ ray (mild)
  - two emission regions?

(1) change of PA direction
(2) increase and then faint of PD

-2°→8° (relativistic aberration)
in Light curve
different behavior between IR-optical and X-γ rays

Two zone leptonic model:
- IR-optical: **far side** (3pc)
- gamma ray: **near side** (in BLR)
→ UV photon for the seed photon

<table>
<thead>
<tr>
<th></th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_b$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>B [G]</th>
<th>$K$ [cm$^{-3}$]</th>
<th>R [cm]</th>
<th>$\delta$</th>
<th>$\Gamma$</th>
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</thead>
<tbody>
<tr>
<td>June (two zones)</td>
<td>internal region</td>
<td>25</td>
<td>610</td>
<td>$3 \times 10^4$</td>
<td>2</td>
<td>3.6</td>
<td>1.45</td>
<td>$3.1 \times 10^5$</td>
<td>1.1$ \times 10^{16}$</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>external region</td>
<td>35</td>
<td>610</td>
<td>$3 \times 10^4$</td>
<td>2</td>
<td>3.35</td>
<td>0.8</td>
<td>$1.05 \times 10^3$</td>
<td>$1.5 \times 10^{17}$</td>
<td>10</td>
</tr>
</tbody>
</table>
Extreme GeV $\gamma$-ray flare


rapid variability (a few hours) at 100 MeV requires a emission region in BLR

Not the unique solution for the emission origin!
PKS 1510-089
Fermi-LAT + MAGIC


- 2012 Feb-Apr, 28 nights
  - HE $\gamma$-ray flare since 2012 Jan
- 6$\sigma$ excess for 21 hrs
- Flux: 4% Crab (>120 GeV)
- Soft spectrum (consistent with HESS)
  - $\Gamma = (3.8 \pm 0.4_{\text{stat}} \pm 0.3_{\text{sys}})$ observed
  - $\Gamma = (2.5 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}})$ EBL corrected

the same emission region of HE and VHE $\gamma$ rays
multi-band light curve


K12 emerging coincident with $\gamma$-ray flare
→ co-spatiality of mm and $\gamma$ ray

3 distinct EVPA rotation > 180°($\sim$380°) but different rate and directions.
emission modeling


leptonic + conical jet

~ 1 pc (hot dust region)

both are OK!

<table>
<thead>
<tr>
<th>model</th>
<th>$\gamma_{\text{min}}$</th>
<th>$\gamma_b$</th>
<th>$\gamma_{\text{max}}$</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$B$</th>
<th>$K$</th>
<th>$R$</th>
<th>$\Gamma$</th>
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<tbody>
<tr>
<td>IR torus</td>
<td>3</td>
<td>9e2</td>
<td>6.5e4</td>
<td>1.9</td>
<td>3.85</td>
<td>0.12</td>
<td>20</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Sheath</td>
<td>800</td>
<td>7e3</td>
<td>5e4</td>
<td>2</td>
<td>3.4</td>
<td>1.3e-2</td>
<td>18</td>
<td>600</td>
<td>2.2</td>
</tr>
<tr>
<td>Spine</td>
<td>800</td>
<td>2.6e3</td>
<td>8e4</td>
<td>2</td>
<td>3.7</td>
<td>6.5e-3</td>
<td>2.5</td>
<td>510</td>
<td>20</td>
</tr>
</tbody>
</table>
emission modeling

one zone leptonic + conical jet

~ 1pc (hot dust region)

both are OK!

~ 18 pc (VLBA core)

Note: PKS 1510-089 shows “steady” VHE γ-ray emission while 3C 279 and PKS1222+216 were detected only in one day.
IC 310: a blazar or radio galaxy?

- AGN in the outskirts of the Perseus cluster (z=0.018) with central BH with mass \( \approx 3 \times 10^8 \) Msun
- Radio, optical and X-ray properties are a mixture of those of FR I and blazars

But,,,

- VLBI (EVN) at 5 GHz: \( \theta_{\text{view}} < 20 \) deg
- Large projected length of kpc radio structure: \( \theta_{\text{view}} > 10 \) deg

**IC 310 might be an intermediate object of the two classes**
Nov 2012 – Jan 2013


• Huge flare on the night of Nov 12/13, 2012
variability on time scales faster than \( \sim 4.8 \text{ min} \approx 0.2R_G \)
Theoretical Interpretation

- **Shock-In-Jet model:**
  \[ R < \delta c \tau_{\text{var}} = \delta \cdot 0.2 \cdot R_g \] (for 4.8 min, \( M_{\text{BH}} = 3 \times 10^8 M_\odot \))

- **Opacity problem:**
  \[ \tau_{\gamma \gamma}(10 \text{ TeV}) = \delta^6 \cdot 1.2 \times 10^5 \] (for 4.8 min, \( L_{\text{syn}} \sim 10^{42} \text{erg/s} \))
  \[ \rightarrow \delta \geq 10 \text{ required} \]

- **Magnetospheric model:**
  by e.g. Levinson & Rieger 2011; Aleksić et al. 2014, *Science*

- Similar to aligned magnetic rotator models for pulsars

- Low accretion rate \( \rightarrow \) small gap height \( \rightarrow \) fast variability

#5768 (15 Jan 14): "DISCOVERY OF VERY HIGH ENERGY GAMMA-RAY EMISSION FROM RBS 0723 WITH THE MAGIC TELESCOPES" (z=0.198)

#5887 (14 Feb 14): "Exceptionally high >100 GeV flux state of 1ES 1011+496" (z=0.212) (together with VERITAS)

#6062 (11 Apr 14): "Discovery of Very High Energy Gamma-Ray Emission from BL Lac object RX J1136.5+6737 by the MAGIC Telescopes" (z=0.1342)

#6349 (28 Jul 14): "Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 With the MAGIC Telescopes" (z=0.944)

#6999 (27 Jan 15): "MAGIC detects Very High Energy gamma-rays from S5 0716+714" (z~0.31?)

#7080 (15 Feb 15): "Discovery of Very High Energy Gamma-Ray Emission from the FSRQ S4 0954+65 with the MAGIC telescopes" (z=0.368)

4 discoveries and 3 flares
S3 0218+357

Detection of the first gravitationally lensed VHE emission: the blazar S3 0218+357

- Detection of the most distant VHE emitting blazar: z=0.944
- Lensing spiral galaxy: B0218+357, z=0.684
- MAGIC cannot spatially resolve the blazar from its lensed images
- Delay of lensed emission: (10.5 +/- 0.4) days (95% CL)
  Biggs et al. 1999
- Previous LAT observations in 2012 (Cheung et al. 2014): increased activity, delayed emission (11.46+/-0.16) days later

Credit: NASA/ESA and the Hubble Legacy Archive
Summary

• the MAGIC performances have improved since 2012 after some hardware upgrades

• FSRQs: $\gamma$-ray emission is not from unique origin
  – both inside and outside the BLR
  – “steady” and “flare” VHE $\gamma$-ray components?

• IC310: variability on time scales $4.8\text{ min} \approx 0.2R_G$
  – pulsar-like emission origin? (Magnetospheric model)

• 4 discoveries of new VHE blazars since 2014
  – S3 0218+357: most distant VHE source at $z=0.944$
    • delay emission (~10 days) by gravitational lensing effect