The MAGIC of FSRQs

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wwwmagic.mppmu.mpg.de
BL Lac objects

- BL Lac is a blazar, where no (or weak) optical emission lines are seen.
- Modelling of BL Lacs is relatively simple, often the emission can be explained with a single blob moving along the jet filled with electrons and magnetic field.
FSRQ objects

- FSRQ is a blazar with pronounced emission lines
- Very luminous (can be observed at high redshift)
- Direct evidences of accretion disk and broad line region
- Complicated sources: need a rich MWL coverage to understand them
VHE gamma-ray emission region in FSRQ

- Gamma-ray emission region in FSRQ:
  - Within the BLR
  - In the radiation field of the dust torus
  - Near the radio core

- The closer to BH the easier to explain variability and luminosity, but the more problematic the absorption of sub-TeV gamma rays
MAGIC: an instrument for VHE gamma ray studies of FSRQs

- FSRQs are intrinsically more powerful than BL Lacs and have higher Compton dominance, but the IC peak is shifted to lower energies.
- FSRQs are a perfect target for *Fermi*-LAT, but difficult for IACTs.
- Need an instrument with excellent low energy performance – MAGIC!
Short history of VHE detections of FSRQs

- **3C 279 (z=0.536):** 2006 (by MAGIC)
- **PKS1510 (z=0.361):** 2009 (by H.E.S.S.), 2012 (by MAGIC)
- **PKS1222+216 (z=0.432):** 2010 (by MAGIC), 2012 (by MAGIC)
- **B0218+357 (z=0.954):** 2014 (by MAGIC)
- **PKS1441+25 (z=0.939):** 2015 (by MAGIC), 2015 (by VERITAS)
- **S4 0954+65 (disputed classification, unknown redshift):** 2015 (by MAGIC)
- **PKS0736+017 (z=0.189):** 2016 (by H.E.S.S.)
- **TON 0599 (z=0.725):** 2017 (by MAGIC), 2017 (by VERITAS)
3C 279 detection revising EBL models

- First FSRQ seen at VHE gamma-ray energies
- It was surprising to detect the spectrum up to 500 GeV despite EBL absorption
- Detection of VHE gamma-ray emission triggered revision of EBL models

Albert et al., 2008, Science, 320, 1752
Fast variability of PKS1222+216

- FSRQ at $z=0.432$
- A VHE gamma-ray flare detected during high GeV state
- Flux doubling time of 10 min puts limits on the size of the emission region (or Doppler factor)

PKS1441+25: FSRQ at $z=0.94$

- GeV flare in April 2015 triggered an intense MWL campaign
- Emission region at fixed distance just beyond the BLR
- Variability caused by changing conditions of the plasma (EED and magnetic field) flowing through the emission region
- IR torus radiation:
  - IC target
  - Internal sub-TeV absorption


Solid line: observed
Dotted: EBL-deabsorbed
QSO B0218+357: gravitationally lensed blazar at $z=0.95$

- The two images (seen in radio and optical) are formed by photons passing at a different distance to the center of the lens.
- The two images arrive at Earth at a different time (~10-12 days).
Something to try at the MAGIC dinner...

- In radio and optical the individual images can be directly seen
- In gamma rays we need to distinguish them by arrival time

Hubble, NASA/ESA

O'Dea et al 1992
B0218+357 – first gravitationally lensed source detected in VHE gamma rays

- In July 2014 *Fermi*-LAT saw a GeV flare from B0218+357
- MAGIC detected a two day long flare at the expected time of arrival (photons seem to follow the same paths in the gravitational field up to at least 250 GeV)
- No increase during the second component of the flare in x-rays and optical range
- The only gravitationally lensed VHE gamma-ray source, nominally the farthest VHE source, one of only a few FSRQ detected in VHE

How to model a gravitationally lensed source?

• Need to take into account:
  – If we are looking at emission of image A, image B, or sum of both
  – (strong lensing) magnification of individual images
  – Absorption in different images and different energy ranges
Two zone model

- “Jet in” zone: larger region within BLR, mostly responsible for low energy emission, quasi-stable and GeV emission at the level of long term Fermi-LAT measurements
- “Jet out” zone: smaller region outside BLR (no strong absorption), mostly responsible for gamma rays (SSC + EC)
PKS1510-089

- Detected in VHE $\gamma$ rays by H.E.S.S. during high optical and GeV state in 2009
- Confirmed by MAGIC during another high state in 2012
- Highly variable in optical and GeV gamma rays, but until 2015 no variability has been observed at VHE

Abramowski et al. 2013
Ahnen et al 2017, 603, 29
What came together with the 2015 flare?

- Follow-up radio observations show a new jet component.
- The zero separation epoch overlaps with the May 2015 high state, however with a large uncertainty.
- Rotation of the optical polarization vector by 100° contemporaneous with the flare.
- Similar behaviour also in 2009 and 2012 VHE detections.

Ahnen et al 2017, 603, 29
A possible scenario of emission for 2015 flare of PKS1510-089

- EC scenario on BLR and dust torus photons
- Emission region placed just outside BLR
- Variability due to changes in $B$ field and electron distribution flowing through the emission region

Ahnen et al 2017, 603, 29
In gray: 2012 emission model (Aleksić et al 2014)
How does the new radio component fit in the picture?
(if it is connected with VHE)

- For a narrow jet (or a narrow spine) the VHE emission can be produced close to the radio core.
- If the emission is produced upstream of the radio core, just beyond the BLR the electrons (after a lot of cooling and adiabatic energy losses) will reach the radio core after:
  \[(1+z) \frac{d_{\text{core}}}{(c\delta\Gamma)} = 21 \left( \frac{d_{\text{core}}}{6.5\text{pc}} \right) \left( \frac{\delta}{25} \right)^{-1} \left( \frac{\Gamma}{20} \right)^{-1} \text{days} \]

Still consistent (even more) with the timescale we saw.

Ahnen et al 2017, 603, 29
How does the optical polarization rotation fit in the picture? (if it is connected with VHE)

- Emission region following a spiral path in mainly toroidal magnetic field (Marscher et al. 2010) – large swings of polarization are possible

- Alternatively light travel effects of axisymmetric emission region pervaded by helical magnetic field (Zhang et al. 2015) – swing of 180 deg is possible (sufficient for 2015 flare)
PKS 1510-089: intranight variability

- In May 2016 H.E.S.S. and MAGIC saw a giant flare during high GeV state
- Intranight variability of VHE emission with time scale of the order of an hour (and a strong hint of switching off of the emission)
- Short variability time scale pushes the far dissipation scenario to the limits

Zacharias et al., ICRC2017
Is PKS1510-089 ever going VHE-quiet?

- Using *Fermi*-LAT we selected nights with low flux > 1 GeV
- Ample MWL coverage from radio to gamma-rays – we select data contemporaneous with MAGIC and taken during low GeV state
Detection of low state VHE gamma-ray emission

- Stacking 75h taken on 76 nights we can detect low state emission with $9.5\sigma$

- The flux is $\sim0.6$ of the one in 2012 high optical/GeV state and a factor 80 below the peak flux of the 2016 flare, but there is no significant change in spectral shape

S4 0954+65: “unknown” blazar

- Unknown redshift
- Uncertain classification (FSRQ or BL Lac)
- Detection of VHE $\gamma$ ray emission during GeV flare in Feb 2015
- Rotation of optical polarization vector by $\sim 100^\circ$
- Emission of a new radio component

Ahnen et al., 2018 (A&A accepted), arXiv:1801.04138
S4 0954+65: broad band modelling

- External Compton scenario on dust torus photons (typical of FSRQ)
- High Compton dominance ($\text{SED}_{\text{IC}}/\text{SED}_{\text{synch}} = 7$)
- If not a FSRQ: synchr. peak at $8 \times 10^{14}$ Hz would classify it as an IBL

Ahnen et al., 2018 (A&A accepted), arXiv:1801.04138
Ton 599: a new member of the family

- A new distant (z=0.72) FSRQ detection in VHE $\gamma$ rays during high optical and GeV state
- Stay tuned for more results from this source

**Detection of very-high-energy gamma-ray emission from the FSRQ Ton 0599 with the MAGIC telescopes**

ATel #11061: Razmik Mirzoyan (Max-Planck-Institute for Physics, Munich), on behalf of the MAGIC collaboration on 15 Dec 2017; 16:21 UT

Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, TeV, VHE, Blazar

Referred to by ATeL #: 11073, 11075, 11624

The MAGIC collaboration reports on the first time detection of very-high-energy (VHE; E>100 GeV) gamma-ray emission from Ton 0599 (RA:+11:59:31.83 DEC:+29:14:43.83 J2000). The object was observed with the MAGIC telescopes for ~1 hour on 2017/12/15 (MJD 58102.2). The preliminary analysis of these data resulted in the detection of Ton 0599 with a statistical significance of about 10 standard deviations. The VHE flux of this detection was estimated to be around $0.15\times10^{-9}$ [ph/cm$^2$/s] (corresponding to about 0.3 CU) above 100 GeV, with a soft spectrum. TON599 is a gamma-ray FSRQ at z=0.72 which is in a remarkably high state from optical to gamma-ray since October 2017 (ATel #10931, #10932, #10937, #10938, #10948, #10949). MAGIC observations on TON 0599 will continue during the next days and multi-wavelength observations are strongly encouraged. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and A. Stamerra (antonio.stamerra@inaf.it)

ATel #11061
(note also ATeL 11075 by VERITAS)
Conclusions

- MAGIC has significantly increased the population of known VHE $\gamma$-ray FSRQs, often due to follow up of GeV high states.
- MAGIC observations of FSRQ expanded the visible VHE gamma-ray universe up to $z \sim 1$.
- Most of the FSRQ flares can be modelled in the EC scenario, with the emission region located beyond BLR in the DT radiation field.
- Quite common (but not always) to have simultaneous ejection of a new radio component, rotation of the optical polarization vector and a VHE $\gamma$-ray flare.
- FSRQ studies with PKS1510-089: MAGIC detected low state, high state, smaller and large flare.
Backup
Magnification

• We *know* the flux magnification ratio of the two images $\mu_A/\mu_B$, but how much is $\mu_A$ and $\mu_B$?
• Radio + optical image can be used for lens modelling, Single Isothermal Sphere model gives simple analytical formulas for flux magnifications in two independent ways:
  - From image positions: $\mu_A = 2.7$, $\mu_B = 0.67$
  - From flux ratio: $\mu_A = 2.8$, $\mu_B = 0.77$
• SIS is a very crude model, but careful lens modelling by Barnacka et al 2016 gave a model consistent with SIS
Absorption at the lens

• Can happen in any of the two images, independently!

• Hints of strong absorption in at least the A image:
  - Large reddening between the two images:
    \[ \Delta E(B-V)=0.90\pm0.14 \] (Falco et al 1999) – Image A is weaker in optical than B!
  - Molecular absorption line gives column density of H2 of 0.5 – 5 \times 10^{22} \text{ cm}^{-2} (Menten & Reid 1996) – would affect soft X-rays
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Model A</th>
<th>Model B</th>
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<td>Bulk Lorentz Factor</td>
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<td>Doppler factor</td>
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<td>Variability Timescale [s]</td>
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<td>Black hole Mass $[M_\odot]$</td>
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<td>Disk luminosity $[\text{erg} \text{ s}^{-1}]$</td>
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<td>Jet Power in Magnetic Field $[\text{erg} \text{ s}^{-1}]$</td>
<td>$P_{j,B}$</td>
<td>$1.0 \times 10^{46}$</td>
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<td>Jet Power in Electrons $[\text{erg} \text{ s}^{-1}]$</td>
<td>$P_{j,e}$</td>
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FSRQs at GeV gamma-rays

- In the 3rd AGN catalog of Fermi-LAT there are 467 FSRQs and 632 BL Lacs.
- FSRQs are intrinsically more luminous than BL Lacs and have IC peak at GeV energies – easy target for Fermi-LAT.

Acknowledgments:
- Ackermann et al 2015
- Fossati et al 1998, D. Horan
FSRQ at (sub-)TeV energies

- Only a handful of FSRQs detected at VHE gamma rays and tens of BL Lacs
- FSRQs are difficult sources for IACTs:
  - Distant (absorption of higher energies in EBL !)
  - Intrinsically steep at sub-TeV energies
  - Need an instrument with an excellent low energy performance: MAGIC
- Observations often during high states at lower frequencies to improve detection chances
B0218+357 flare in 2014

- On July 13/14 Fermi-LAT saw a flare from B0218+357, not as strong as in 2012, but with a much harder spectrum.
- Flare lasted for 2 days more and then subsided.
- MAGIC couldn't observe the original flare because of the full moon period.
- Observations were scheduled during the expected delayed emission.
- The two nights around the time of the expected delayed emission led to a detection with $5.7\sigma$ significance.


Expanded VHE sky from $z = 0.5-0.6$ to 0.94.
In May 2016 another gamma-ray high state happened

H.E.S.S. and MAGIC detected a giant flare from PKS1510

Fermi-LAT showed gradual hardening of the emission

Also simultaneous somewhat higher optical state

Zacharias et al., ICRC2017
PKS1510-089 GeV flux distribution
PKS1510-089 low state
VHE light curve
Model for low state
S4 0954+65 a blazar with many unknowns

- Disputed redshift: $z=0.368$ or $z>0.45$
- Uncertain classification
  - Small equivalent width of the emission lines: **blazar-like**
  - Broadband spectral features (flatter index in X-rays and $\gamma$ rays, hint of blue-bump): **FSRQ-like**
- Until 2015 not detected at VHE $\gamma$ rays
S4 0954+65: VLBA images after the flare

VLBA images show an appearance of a new radio component (K15) at the time of the flare

Ahnem et al., 2018 (A&A accepted), arXiv:1801.04138