Mrk421 and Mrk501 as high-energy physics laboratories to study the nature of blazars

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Many Instruments/collaborations: Fermi, MAGIC, VERITAS, FACT, NuSTAR, RXTE, Swift, GASP-WEBT, F-GAMMA, SMA, VLBA, Metsahovi, OVRO, UMRAO ...

• Introduction: the challenge of studying blazars
  ➔ Extensive MW campaigns on Mrk421 and Mrk501
• Some highlighted results
  ➔ Peculiar behaviors (during low activity)
• Conclusions
• Introduction: the challenge of studying blazars
  → Extensive MW campaigns on Mrk421 and Mrk501
The CHALLENGE of studying blazars

Many basic open questions... that persist since the 80s
→ e.g. see Talk by Esko Valtaoja
   (Jets conference in Malaga, May 2016: http://jets2016.iaa.es )

From observational perspective, there are two major practical challenges
a) Blazars emit over a very wide energy range
   (from radio to very high energy gamma-rays)
   → Poor sensitivity at gamma-ray energies until last decade
b) Blazar emission is variable on very different timescales
   (from years down to minutes)

→Need radio-to-gamma MW campaigns lasting many years
   → big effort needed, NOT possible for many objects
   →Which objects should we study?
Why studying Mrk421 and Mrk501?

- **Bright blazars**
  - Easy to detect with IACTs, *Fermi*, and X-rays, Optical, radio instruments in short times
  - “Relatively Easy” to characterize the entire SED in every “shot”
  - Can study the evolution of the entire SED

- **Nearby blazars** *(z~0.03; ~140 Mpc)*
  - Imaging with VLBA possible down to scales of <0.01-0.1 pc (<100-1000 \(r_g\))
  - Minimal effect from EBL (among VHE blazars), which is not well known
    - systematics for VHE blazar science

- **No strong BLR effects** *(another unknown... composition, shape...)*
  - Fewer additional uncertainties than in FSRQs

**In summary:**

- Mrk421 and Mrk501 are among the “easiest” blazars to study
  
  *It is more difficult to study other blazars that are farther away, dimmer, or have more complicated structures*

They can be used as high-energy physics laboratories to study blazars.
Why studying Mrk421 and Mrk501?

Mrk421 as possible source of PeV neutrinos and 30 EeV CR

See talks by P. Padovani and A. Mastichiadis
(Jets conference in Malaga, May 2016: http://jets2016.iaa.es)

Petropoulou et al, 2015
MNRAS 448, 2412

See also Dermer & Razzaque 2010,
ApJ 724, 1366
Extensive MW Campaigns on Mrk421 and Mrk501

A multi-instrument and multi-year project

Since 2009, we have substantially improved TEMPORAL and ENERGY coverage of the sources in order to obtain SEDs as simultaneous as possible, as well as to be able to perform multi-frequency variability/correlation studies over a long baseline and correlate with high resolution radio images and polarizations (to learn about the jet structure)

• More than 25 instruments participate, covering frequencies from radio to VHE

Radio: VLBA, OVRO, Effelsberg, Metsahovi...
mm: SMA, IRAM-PV
Infrared: WIRO, OAGH
Optical: GASP-WEBT, GRT, Liverpool, Kanata...
UV: Swift-UVOT
X-ray: (RXTE), Swift-XRT, NuSTAR
Gamma-ray: Fermi-LAT
VHE: MAGIC, VERITAS, FACT

Monitored regardless of activity (increase coverage during flares)
→ observed every few days for about half year (every year !)
Extensive MW Campaigns organized on Mrk421/Mrk501

Mrk421 (Jan19th, 2009-Jun1st, 2009: 4.5 months)- Planned observations: every 2 days

Mrk501 (Mar15th, 2009-Aug1st, 2009: 4.5 months) - Planned observations: every 5 days

Mrk421 (Dec8, 2009-Jun20, 2010: 6 months)- Planned observations: every 1-2 days

Mrk421 (Dec1, 2010-Jun15, 2011: 6 months)- Planned observations: every 2 days

Mrk501 (March1, 2011-Sep1,2011: 6 months) - Planned observations: every 3 days

Mrk421 (Dec23, 2011-May31, 2012: 5.5 months)- Planned observations: every 2 days

Mrk501 (Feb15, 2012-June31,2012: 4.5 months) - Planned observations: every 4 days

Mrk421 (Dec, 2012-May, 2013: 6 months)- Planned observations: every 2 days

Mrk501 (April, 2013-Sep,2013: 5 months) - Planned observations: every 4 days

Mrk421 (Dec, 2013-May, 2014: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2014-Aug,2014: 5 months) - Planned observations: every 3 days

Mrk421 (January, 2015-June, 2015: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2015-June, 2015: 4 months)- Planned observations: every 5-10 days

Mrk421 (Dec, 2015-June, 2016: 6 months)- Planned observations: every 2 days

Mrk501 (March, 2016-Sep, 2016: 6 months)- Planned observations: every 4 days
Extensive MW Campaigns on Mrk421 and Mrk501

LHC vs Mrk421/Mrk501

ATLAS/CMS
LHCb + Alice

MAGIC/VERITAS/Fermi
NuSTAR/Swift + Optical + radio

LHC comes with “adjustable knobs” (controlled environment) and measure the interactions directly; while for Mrk421/Mrk501 we only can observe it in an indirect way (through secondary products) and aim at identifying when the “knobs changed”

In both cases we learn many things by using these “extreme particular accelerators”; and surely that requires “observing” over many years in order to integrate over sufficient data/effects.
As we collect MW data on Mrk421/Mrk501 we learn new things about them, which led to several publications with data from single campaigns (and often with only a small fraction of the campaign data).

So far we have 13+1 publications

Koyama, S., et al., 2015, PASJ, 164
Aleksic et al, 2015, A&A 573, 50
Aleksic et al., 2015, A&A 575, 128
Aleksic et al., 2015, A&A 578, 22
Aliu et al., 2016, accepted in A&A
Ahnen et al., 2016, submitted to A&A

4 with small dataset (focused on radio)

9+1 with extensive MW dataset (includes TeV)

In this talk, I will report some results from these papers, as well as from the campaign on Mrk501 during 2012 (→ manuscript under internal review within various groups)
• Some highlight results from the campaigns
SED peak positions shifted to lower energies by factor $\sim 10$

Peak position at $\sim 10^{16}$ Hz ($\sim 40$ eV)
First time we see such big shift
→ “HBL moving towards IBL”

(typical state)

Low activity in blazars is as interesting as the high activity (flares)
But can only be studied in detail on the brightest sources and with highly sensitive instruments

Balokovic et al., 2016
ApJ 819, 156

Mrk421
MW2013

2013 Jan 10
(MJD 56302)
SED peak positions shifted to lower energies by factor $\sim 10$

Peak position at $\sim 10^{16}$ Hz ($\sim 40$ eV)

First time we see such big shift

$\Rightarrow$ “HBL moving towards IBL”

(typical state)

Low activity softened the X-ray and VHE spectra, but did not bring spectral cutoffs.

$\Rightarrow$ Electrons accelerated to highest energies
X-ray spectral shape vs. flux

NuSTAR spectra from Balokovic et al., 2016
*ApJ* 819, 156

RXTE-PCA spectra from Giebels et al., 2007, *A&A*, 462, 29

Broken power law, with indices $\Gamma_1$ and $\Gamma_2$
X-ray spectral shape vs. flux

Saturation at low fluxes

Harder when brighter (typical behaviour)

Saturation at high fluxes
Variability vs. Energy

Variability quantified following prescription from Vaughan et al. 2003

Highest variability occurs at X-ray and VHE

For each bump, variability increases with energy

Double-bump structure (same as SED)

Highest $F_{\text{var}}$ at X-rays and VHE

$F_{\text{var}} = \sqrt{\frac{S - \langle \sigma_{\text{err}} \rangle^2}{\langle \text{Flux} \rangle^2}}$
“Falling segments” of the low- and high-energy bumps are more variable than the “rising segments” (ALWAYS!!)

→ Within the Synchrotron self-Compton scenario, the X-ray and VHE emission is produced by the highest-energy electrons
Variability vs. Energy

Variability quantified following prescription from Vaughan et al. 2003

\[ F_{\text{var}} = \sqrt{\frac{S - \langle \sigma_{\text{err}} \rangle^2}{\langle \text{Flux} \rangle^2}} \]

2009 (low) Mrk421

Aleksic et al., 2015
A&A 575, 128

2010 (flare) Mrk421

Aleksic et al., 2015
A&A 578, 22

Typical characteristic of Mrk421, in both high and low state
$F_{\text{var}}$ with energy and the hardening of the X-ray spectra with increasing flux suggest that the variability in the emission of Mrk 421 is produced by chromatic changes in the electron energy distribution, with the highest-energy electrons varying the most.

The saturation of the X-ray spectral shape at the extremely high and low X-ray fluxes indicates that, for these periods of outstanding activity, the flux variability is instead dominated by other processes that lead to achromatic variations in the X-ray emission.

→ Mrk421 shows different characteristics (on different activity levels)
Comparison of variability between the two archetypical TeV blazars: Mrk421 vs. Mrk501

Typically, we measure that:

- $F_{\text{var}} (\text{Mrk421})$: clear double-peaked structure, $F_{\text{var}} (\text{X-rays}) \sim F_{\text{var}}(\text{VHE})$
- $F_{\text{var}} (\text{Mrk501})$: monotonic increase with energy, $F_{\text{var}}(\text{X-rays}) < F_{\text{var}}(\text{VHE})$

→ Note observational bias due to lack of complete energy coverage

→ e.g. $F_{\text{var}}$ at Hard X-rays ($>100$ keV) expected to be larger
Mrk501 suffers a personality crisis (in 2012)

• VERY hard spectral index, regardless of activity (during MW 2012)
  X-ray $\Gamma > -2$
  gamma-ray $\Gamma \gtrsim -2$

Typical Mrk501 X-ray PL Index $\sim 2.0$

Typical Mrk501 VHE PL Index $\sim 2.5$

X-ray (Swift)

VHE (MAGIC+VERITAS)

Preliminary
Mrk501 has shown X-ray and VHE spectral variability during flares

(Historical) flare in 1997


(fast variability) flare in 2005


Hard spectra in Mrk501 not observed during low states, and VHE spectral index NEVER observed harder than 2 (until year 2012)
Mrk501 suffers a personality crisis (in 2012)

- VERY hard spectral index, regardless of activity (during MW 2012)
  - X-ray $\Gamma > -2$
  - gamma-ray $\Gamma \geq -2$

Typical Mrk501 X-ray PL Index $\sim 2.0$
Typical Mrk501 VHE PL Index $\sim 2.5$

→ Mrk 501 behaved like an Extreme HBL!

Similar X-ray/VHE spectra as
1ES 0229+200, 1ES 0347-121

Being "extreme HBL" may be a temporal state, rather than an intrinsic characteristic of a blazar.
3 – General Conclusions

The MW campaigns on Mrk421 and Mrk501 are a multi-year AND multi-instrument program that is running since 2009. **Deepest Temporal and Energy coverage of any TeV object**

*Many interesting (novel) results*
  -> *Some results already published, some others in the publication pipeline*

Large complexity in the temporal evolution of the broadband SED
  -> *Complicated “source personalities”:*
     Mrk421: HBL trying to become IBL
     Mrk501: HBL became EHBL (in2012) during non-flaring activity
  -> *Are these recurrent episodes? Do they occur on other blazars?*

**We can use Mrk421 and Mrk501 as our blazar physics laboratory**
Lessons learnt may be applied to other blazars (farther away or weaker)
Backup slides
Large intra-model and inter-model degeneracy for fitting single broadband SEDs

Mrk421 SED described with a
Leptonic scenario

Figure 11. SED of Mrk 421 with two one-zone SSC model fits obtained with different minimum variability timescales: $t_{\text{var}} = 1$ day (red curve) and $t_{\text{var}} = 1$ hr (green curve). The parameter values are reported in Table 4. See the text for further details.

Mrk421 SED described with a
Hadronic scenario

Figure 9. Hadronic model fit components: $\pi^0$-cascade (black dotted line), $\pi^\pm$ cascade (green dash-dotted line), $\mu$-synchrotron and cascade (blue triple-dot-dashed line), and proton synchrotron and cascade (red dashed line). The black thick solid line is the sum of all emission components (which also includes the synchrotron emission of the primary electrons at optical/X-ray frequencies). The resulting model parameters are reported in Table 3.


Multi-band variability is key to distinguish between models
Large intra-model and inter-model degeneracy for fitting single broadband SEDs

Ahnen et al. Submitted to A&A

Fig. 15. Modelling of the SED of Mrk 501 compiled from measurements collected during the high state observed around MJD 54973. Two-zone SSC models have been inspected following the grid-scan strategy. The total emission (solid lines) is assumed to stem from a first quiescent region (black dot-dashed lines) responsible for the average state (Abdo et al. 2011) plus a second emission region (dashed lines). Highlighted are the model with the highest probability of agreement with the data (red), a model featuring a prominent high-energy component in the EED (orange), and a model with low Doppler factor (cyan, $\delta = 5$). Model curves underlaid in grey show the bands spanned by models with a fit probability better than $0.9 \times P_{\text{best}}$, $0.5 \times P_{\text{best}}$ and $0.1 \times P_{\text{best}}$, respectively. The data points have been corrected for EBL absorption according to the model by Franceschini et al. (2008).
Large intra-model and inter-model degeneracy for fitting single broadband SEDs

Ahnen et al. Submitted to A&A

Fig. 14. Distributions of the investigated models in the individual model parameters for the dense parameter grid and a two-zone scenario for MJD 54973. The X-axis of each plot spans over the probed range for each parameter. Shown are the model with the highest probability of agreement with the data and all models which populate the given probability bands (see legend).
Mrk421 data from Jan/Feb/March 2013

First MW campaign on Mrk421 that includes NuSTAR (3-80 keV)

~TeV  
Balokovic et al., 2016  
*ApJ* 819, 156

~GeV

~10 keV

At VHE it was typically below 0.5 Crabs, with fluxes as low as 15% Crab

~ 1 keV

Among lowest fluxes ever reported at X-ray and VHE

~1 eV

~10 microeV
SED peak positions shifted to lower energies by factor ~10


Peak position at ~$10^{16}$ Hz (~40 eV)
First time we see such big shift → “HBL moving towards IBL”

Spectrum can be described with a one-zone SSC model

Main Differences with respect to typical SED can be explained (mostly) with (much) lower electron energies, smaller size R, and higher B field

However, in the paper we argue that the observed variability patterns suggest that a multi-zone scenario is preferred
NuSTAR LC 10 min bins intranight variability, in most nights

Shaded areas depict time intervals with MAGIC/VERITAS observations.
NuSTAR LC 10 min bins intranight variability, in most nights

Large/smooth variations in the count rate can be described with a timescale of 6-12 hours

Balokovic et al., 2016 ApJ 819, 156

Shaded areas depict time intervals with MAGIC/VERITAS observations
NuSTAR X-ray LC (during tens of hours) on Mrk421 with ~30-50% peak to peak variations is similar to multi-instrument optical LC on 0716+714 during 78 hours.

~30% peak to peak variations,

In both cases, these LCs suggest a superposition of emission from various regions

→ During strong flares, a single region may dominate
Correlations

Mrk421
MW 2009

Low state and little variability in X-ray/VHE (no flares !!)

X-ray and VHE are correlated
ALSO on long-term timescales and during the low activity (no flaring activity)

→ Similar processes during flaring and non-flaring activity
Correlations

Clear correlation between X-rays and VHE fluxes (on even lower flux)

→ Correlation on strictly simultaneous observations and nightly averages
→ There is a change in slope with the X-ray energy band considered
  → Linear behaviour with soft X-rays (*inverse-Compton scattering in Klein-Nishina*)
  → Less than linear with the hard X-rays (7-30 keV)
  → The super-high energy electrons contribute less to >200 GeV flux

Mrk421 MW 2013
Balokovic et al., 2016 ApJ 819, 156
**Correlations**

**Balokovic et al., 2016**

*ApJ 819, 156*

X-ray and UV fluxes do NOT correlate

Lack of overall correlation optical/X-ray is common in 2009 (Aleksic et al., 2015, A&A 575, 128),
In 2010 (Aleksic et al., 2015, A&A 578, 22)
In 2007-2015 *(See Poster from M.I. Carnerero)*

→ Two different components

OR

→ Variability mostly on high-E electrons

→ Low-E electrons vary independently

Marginal correlation (2.5-3 sigma) of Fermi GeV and UV fluxes

→ Expected from SSC models, where both optical/UV and MeV/GeV fluxes are related to low energy electrons
Correlations

Correlation between radio (VLBA 43 GHz) and gamma (>0.1 GeV) also detected for Mrk421 during non-flaring (but variable !!) activity

- Lico et al., 2014 (A&A 571, 54)

Fig. 7. Discrete cross-correlation function between the $\gamma$-ray and the 43 GHz radio light curves (black curve). The gray curves represent the 99.7% confidence limits relative to stochastic variability, obtained from the combination of different power spectral density slopes. See section 3.5 for more details.