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The blazar Mrk 421: a short multifrequency review

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Abstract. Mrk 421 is one of the best studied blazar in Very High Energy (VHE) gamma-rays, with several multifrequency campaigns performed in order to investigate possible correlations in the broad band Spectral Energy Distribution variability. The main properties of Mrk 421 as inferred by multifrequency campaigns will be reviewed, with particular emphasis to those derived from the June 2008 campaign which involved simultaneous data in Optical/UV, X-ray, gamma-ray and Very High Energy gamma-ray energy bands.

1. Introduction

Mrk 421 is one of the best studied BL Lac objects in the UV and X-ray energy bands. It is also the first object detected at $E > 500$ GeV (Punch et al. 1992). It has the typical Spectral Energy Distribution (SED) of the High energy peaked BL Lac objects (Padovani & Giommi 1995), which typically appear double-peaked in a $\nu F \nu$ representation, with a synchrotron peak at soft X-rays and a second high energy component peaking at GeV-TeV energies. The GeV-TeV peak is commonly interpreted as inverse Compton scattering of the synchrotron photons by the same population of relativistic electrons Synchrotron Self Compton (SSC; Maraschi et al. 1999); this scenario is supported by the observed correlated X-ray/TeV variability (Fossati et al. 2008, Wagner et al. 2008). On the other hand, hadronic models cannot a priori be ruled out. In this scenario, proton-initiated cascades and/or proton-synchrotron emission are invoked to explain the GeV-TeV peak (Aharonian 2000, Mücke et al. 2003); in this case, no correlation between X-ray and TeV variabilities has to be expected. Moreover, leptonic and hadronic scenarios for HBLs predict different properties of the γ-ray emission as compared to the emission in the other energy bands. In particular, the hadronic models (as compared with the SSC ones) predict a flatter slope of the ~ 100 MeV IC emission than that of the synchrotron emission in the optical, UV energy bands. In order to unveil the existence of correlated variability between X-ray and VHE gamma-ray observations, several multifrequency campaigns were performed in the past. Fossati et al. 2008 performed a 1-week long simultaneous observations at 2-60 keV X-rays (RXTE) and TeV γ-rays (Whipple and HEGRA) in 2001, finding strong variations in both X-ray and gamma-ray bands, which were highly correlated. In particular, these correlated variations seem to occur linearly, but it is worth noting that a differece between the correlations observed on short (hours) and longer (days) timescales occurred, being the first quadratic. By revisiting the data of this multifrequency campaign, Katarzyński & Walczewska 2010 found that single zones

Send offprint requests to: I. Donnarumma models are not able to explain quadratic ore more than quadratic correlation between the X-ray and gamma-ray emissions occurring on hour timescales.

Other interesting properties of Mrk 421 have been understood by means of a monitoring in soft X-rays (Tramacere et al. 2009) and at VHE gamma-rays (Aleksic et al. 2010). In particular, the observed X-ray spectra appear curved, well described by a log-parabolic shape (Tramacere et al. 2007) and the X-ray emission peak well correlates with the peak energy. This may be explained in the framework of synchrotron process involving variations of the electron Lorentz factor γ_{break}. Moreover, the synchrotron curvature decreases as the energy peak increases: this spectrum variability is more likely associated with the statistical or stochastic acceleration mechanisms. In this case, the curvature decreases as the gain of the acceleration process increases.

A similar analysis carried out at VHE gamma-rays by assuming a log-parabolic shape (Aleksic et al. 2010) showed indications of rising peak energy with increasing flux as observed in the case of the synchrotron emission peak.

In the following sections the June 2008 multifrequency campaign on Mrk 421 will be presented, describing the broad band dataset and the theoretical findings derived from them.

2. The June 2008 multifrequency campaign

2.1. AGILE observations

During a Target of Opportunity (ToO) activated in June 2008 to follow a VHE γ-ray flare from the blazar W Comae, AGILE (Tavani et al. 2009) detected a flare of Mrk 421 in the energy range 20-60 keV with its hard X-ray monitor, SuperAGILE (Feroci et al. 2007). The source was detected at a flux of $\sim$ 30 mCrab that is $\sim$ 1 order of magnitude greater than the one in quiescence state. In the following days, its flux increased up to $\sim$ 55 mcrab (see blue points in Fig. 1, bottom panel in the left). The hard X-ray data were complemented by Swift/BAT (15-50 keV) data which clearly showed that SuperAGILE detected the maximum brightness of the flare. No significant γ-ray emission above 100 MeV was observed by AGILE-GRID integrating on daily-time scale across the hard X-ray flare. By integrating the data collected during the whole duration of the observations (1-week), Mrk 421 was detected by the GRID ($E > 100$ MeV) with a flux of $(42 \pm 13) \times 10^{-8}$ photons cm^{-2} s^{-1}, consistent with the highest flux observed by EGRET.

2.2. Swift observations

In order to follow the hard X-ray flare detected by SuperAGILE, 5 ks ToO observations were performed between 2008 June 12 and 13. The *Swift XRT* spectrum in the energy range 0.7-9.0 keV was combined with the one provided by SuperAGILE and then fitted by means of a log-parabolic model ($F(E) = KE^{-a-b\log(E)}$, see Massaro et al. 2004, Tramacere et al. 2007), resulted in the following values of its parameters $a = 1.65 \pm 0.012$, $b = 0.37 \pm 0.010$. These values implied a peak energy $\sim$ 3 keV, F(2-10 keV) $=2.56 \times 10^{-9}$ erg cm^{-2} s^{-1} and F(20-60 keV)$=5.7\times10^{-10}$ erg cm^{-2} s^{-1}. The RXTE All-Sky Monitor data were used to complement the *Swift* observations. These showed (left, bottom panel in Fig. 1) that *Swift* catched the maximum brightness of the source in soft X-rays.

Moreover, the *Swift*/XRT observations showed also variability on hr timescale, in particular a spectral hardening was present in the X-ray emission across the June 12th flare. This was confirmed by the behavior of the hardness ratio between hard (15-60 keV) and soft (2-12 keV) X-rays. As it is shown in Donnarumma et al. 2009 (bottom panel in their Fig. 1), the second peak is significantly harder than the first one. Hence, it seems that the source underwent the hardest part of this double-humped flare just during the AGILE gamma-ray detection.

2.3. GASP-WEBT and UVOT observations

Mrk 421 is one of the 28 blazars monitored by the GLAST-AGILE Support Program (GASP; Villata et al. 2008) of the whole Earth Blazar

Telescope (WEBT). In Fig. 1, 1st panel, we show the R-band optical light curve between 2008 May 31 - June 24, obtained after the subtraction of the emission of the host galaxy and nearby objects. During the Swift pointing on June 12-13, the UVOT instrument also observed Mrk 421 in the UVW1 and UVW2 photometric bands.

2.4. TeV observations

Mrk 421 was monitored by the VERITAS (Arizona, USA; Acciari et al. 2008) and MAGIC (Canary islands, Spain; Baixeras et al. 2008) telescope systems for 1.17 hr and 2.95 hr, respectively, from May 27 to June 8. Later observations were prevented because of moonlight constraints. The object was clearly detected during each nightly observation, with a total significance of 44 sigma (VERITAS) and 66 sigma (MAGIC). The combined flux $E > 400$ GeV showed a transient peak near MJD 54622 (right, bottom panel in Fig. 1). Spectral data on June 6 where used to build a spectral energy distribution. The derived spectrum is corrected for the extragalactic background light attenuation according to Raue & Mazin 2007.

3. Discussion

During the June 2008 campaign, Mrk 421 showed variability patterns across the overall broad band emission, from Optical to TeV energy ranges. We modeled two Spectral Energy Distributions (SEDs) by fixing two time periods (derived by the largest simultaneity of the data): the first (*period 1*), 2008 June 6, with the inclusion of optical, X-ray (XTE and BAT) and TeV data (VERITAS); the second (*period 2*) 2008 June 915, including optical, UV, X-rays (XRT and SuperAGILE) and gamma-ray data (AGILE). The broad band variability patterns appear to be in overall agreement with the modeling with a standard 1-zone SSC model. The optical, soft and hard X-ray bands strongly constrain the SED around the synchrotron peak, and its daily variability reveals the physical processes of Mrk 421. Possible correlated variability is shown in Fig. 1 be-

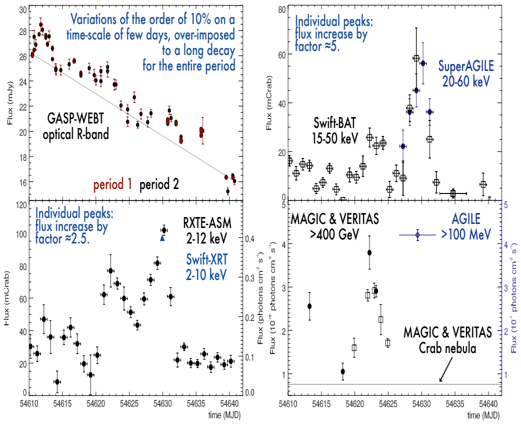

Fig. 1. *left*: Optical-*R* light curve from GASP-WEBT in the period May 31-June 24 (top panel); RXTE/ASM light curve over the same period; *right*: SuperAGILE (blue circles) and BAT (empty black squares); AGILE and TeV data (black squares and circles, MAGIC and VERITAS respectively). Adapted from Donnarumma et al. 2009.

tween the optical (an overall decreasing trend with superimposed spikes of emission), the X-rays (several emission peaks lasting few days), and the high-energy parts of the spectrum. Based on the physical constraints obtained for the synchrotron peak, we modeled both the gamma-ray and VHE-ray emissions.

We considered two possible scenarios to interpret this variability. The first (A) invokes a hardening of the electrons distribution caused by particle acceleration, which predicts a comparable X-ray and TeV variations because of the Klein-Nishina regime. The second (B) requires a change of the comoving particle density, as a consequence of additional particle injection/loss by shock processes; in this case a larger flux variability at TeV energies than in the X-rays ($\Delta F/F$ larger by factor 2) is expected. Our data appear to support case (A). In Fig. 2 is shown the observed SEDs and our SSC modeling for period 1 and period 2.

Very interesting is also the long-term decay observed in optical, but not in X-rays/TeV. This may suggest a further scenario in which the inner jet responsible for the X-ray emission is only partially transparent to the optical radiation. The signature of the X-ray activity observed in optical would come from the inner region, but it is diluted from the Optical emission coming from the outer region (mrk 501, in Villata et al. 1999). Finally, the 2-10 keV flux measured by XRT on June 12-13, $\sim 2.6 \times 10^{-9}$ erg cm^{-2} s^{-1}, is higher than all previous observations (Fossati et al. 2008, Lichti et al. 2008) and the derived peak synchrotron energy of ~ 3 keV is higher than typical values of 0.5-1 keV for this source. See Donnarumma et al. 2009 for a deeper discussion.

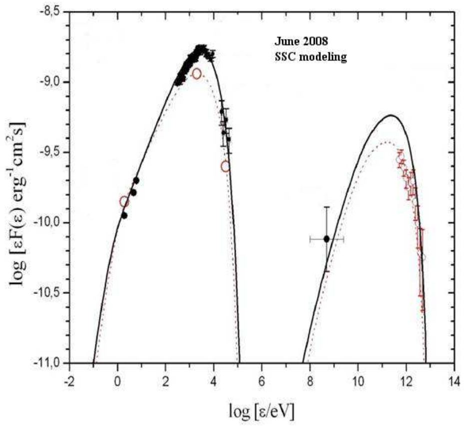

Fig. 2. Data and models of the Spectral Energy Distributions of Mrk 421 for period 1 (red) and period 2 (black). Adapted from Donnarumma et al. 2009.

4. Conclusions

In the following, a summary of the main conclusions derived from the June 2008 multifrequency campaign, as compared with those of past campaigns, are reported:

- The June 2008 observations provided evidence that X-rays and VHE gamma-rays correlate (leptonic model at work) at least during the flaring activity, in agreement with the previous findings of Fossati et al. 2008, Katarzyński & Walczewska (2010). However, it has to be underlined that a firm conclusion on this correlation was prevented by the lack of VHE gamma-rays data simultaneous with the brightest X-ray flare from Cherenkov observatories. Neverthless, during the brightest X-ray flare the full coverage Air Shower ARGO/YBJ in Tibet was monitoring the source as it is doing since 2007 December (Aielli et al. 2010). These data allowed to establish that a positive correlation was present between soft X-ray and VHE gamma-ray emissions during the June 2008 flare.
- As observed during the March 2001 campaign, the daily variability observed during the June 2008 flare seems to be not quadratic, which combined with the spectral hardening observed in X-rays, supports the interpretation that the flaring activity is mainly dominated by acceleration mechanisms (because of the Klein-Nishina regime) at least on this timescale. This seems to be confirmed by the ARGO/YBJ flux across the brightest flare (June 11-13) which, although slighly higher (6 times the Crab flux) with respect to our theoretical prediction in period 2, supports the linear correlation and then the dominance of acceleration processes during the flare.
- The peak energy Ep ~ 3 keV corresponding to the brightest flux ever observed before in 2-10 keV (2.6×10^{-9} erg cm^{-2} s^{-1}) agrees with the steeper positive correlation found by Tramacere et al. (2007) between the Synchrotron emission peak and the energy peak. This represents a further evidence that change in γ_{break} leads the flaring activity of Mrk 421.
- The combined soft/hard X-ray spectra (Swift/SuperAGILE) confirm that the Mrk 421 spectrum is curved in X-rays.
- Investigating shorter time scale variability would be te the key to disentangle between evidence of more than 1-zone in SSC model (Katarzyński and Walczewska 2010).
- Sinergy between X-ray and GeV-TeV observatories is needed to further constrain all the processes at work in this kind of object.

Very high sensitivity on short time scales (less than hours) is also needed.

5. Discussion

JOERN WILMS: What about the radio emission during the June 2008 campaign?
IMMACOLATA DONNARUMMA: Radio data were not included in this campaign. Concerning the radio emission, I would expect it followed the long term decay observed in the optical band, because both cover the raising tail of the synchrotron emission.
GIAMPIERO TAGLIAFERRI: You showed that the X-ray spectrum gets harder when the flux increases. What about the synchrotron peak, does it go to higher energies when the flux increases?
IMMACOLATA DONNARUMMA: Yes, the synchrotron peak moves towards higher energies when the flux increases; it seems to be the same also for the VHE gamma-ray peak, probing the inverse Compton emission region.

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