Mrk 421 active state in 2008: the MAGIC view, simultaneous multi-wavelength observations and SSC model constrained

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ABSTRACT

Context. The HBL–type blazar Markarian 421 is one of the brightest TeV gamma–ray sources of the northern sky. From December 2007 until June 2008 it was intensively observed in the VHE ($E > 100$ GeV) band by the single dish Major Atmospheric Gamma–ray Imaging Cherenkov telescope (MAGIC-I).

Aims. We aimed to sample the evolution of the source emission at VHE and in other bands, and to model the broad band spectral energy distribution (SED) of selected states, reconstructed by means of sets of multi–wavelength (MWL) data observed simultaneously.

Methods. We performed a dense monitoring of the source in VHE with MAGIC-I, collecting also complementary data in soft X–rays and optical–UV bands; then, we modeled the SEDs derived from simultaneous MWL data within the Synchrotron Self–Compton (SSC) framework.

Results. The source showed intense and prolonged $\gamma$–ray activity during the whole period, with integral fluxes ($E > 200$ GeV) seldom below the level of Crab Nebula, and up to 3.6 times this value. Eight datasets of simultaneous optical–UV (KVA, Swift/XRT) and MAGIC-I VHE data were obtained during different outburst phases. Robust constraints could be put to the physical parameters of the jet, interpreting the spectral energy distributions obtained within the framework of a single–zone SSC leptonic model.

Conclusions. The main outcome of the study is that within the homogeneous model high Doppler factors ($40 \leq \delta \leq 80$) are needed to reproduce the observed SED; but this model can not explain the observed short time scale variability, while it can be argued that inhomogeneous models could allow for less extreme Doppler factors, larger magnetic fields and shorter electron cooling times compatible with hour or sub-hour scale variability.

Key words. Gamma-rays: observations — Radiation mechanisms: non-thermal — Galaxies: BL Lacertae objects — individual:Mrk 421

1. Introduction

Blazars, a common term used for flat spectrum radio quasars (FSRQ) and BL Lacertae objects, constitute the subclass of Active Galactic Nuclei (AGN) that is most commonly detected at VHE. In these sources the dominant radiation component originates in a relativistic jet pointed nearly towards the observer. The double–peaked Spectral Energy Distribution (SED) of blazars is attributed to a population of relativistic electrons spiraling in the magnetic field of the jet. The low energy peak is commonly referred to synchrotron emission, from its spectrum and polarization. The second, high energy peak is attributed to inverse Compton scattering of low energy photons in leptonic acceleration models (Maraschi et al., 1992; Dermer & Schlickeiser, 1993; Bloom & Marscher, 1996). Alternative models invoking a relevant contribution from accelerated hadrons can also sufficiently describe the observed SEDs and light curves (Mannheim, 1993; Mücke et al., 2003 but see Sikora et al., 2008 on FSRQs).

Blazars are highly variable in all wavebands and the relation between variability in different bands is a key element in discriminating between different models. For instance, homogeneous leptonic models foresee correlated variability between e.g. X–rays and $\gamma$–rays which is already observed in High frequency peaked BL Lacs (HBL; see e.g. Fossati et al., 2008 on Mrk 421 itself). On the other hand phenomena such as the “orphan” flare from 1ES1959+650 reported in Krawczynski et al., 2004 are harder to explain within this frame.

Amongst blazars, HBLs are the observationally favored subsample in the VHE domain, as the high energy bump peaks at GeV–TeV energies, while the low energy peak is located at UV to X–rays energies (Padovani, 2007). This makes HBLs, such as Mrk 421, ideal targets for sensitive, low energy threshold Imaging Air Cherenkov Telescopes (IACT) such as MAGIC-I, in combination with soft X–ray telescopes, that observe the synchrotron bump instead; this combination of instruments samples the source SED unraveling the regions of the two peaks, the most valuable tracers of the source state.

Mrk 421 is one of the closest ($z = 0.031$; de Vaucouleurs et al., 1991) and brightest extragalactic TeV sources; therefore the first detected (Punch et al., 1992) and one of the best studied. The VHE integral flux can vary from a few tenths to a few Crab Units (e.g., see Donnarumma et al., 2009; Hsu et al., 2009 or Piché, 2009), on time scales as short as 15 minutes (Gaidos et al., 1996). The $\nu F(\nu)$ distribution of the emitted photons follows the standard “double-bumped” shape, but varies significantly from low activity states to the most intense flares, on time scales that in X-rays can be of few hours (Ushio et al., 2009). The low-energy bump peaks in the $0.1 \sim 10$ keV range (see e.g. Fossati et al., 2008), as usual for HBLs; the maximum of the high energy bump is usually found below 100 GeV, but can as well move around according to the state of the source (Albert et al., 2007a). This peculiar SED shape favors multi–wavelength studies that exploit the MAGIC-I sensitivity and low energy threshold in VHE, and soft X-ray telescopes. MAGIC-I can detect Mrk 421 at the 5$\sigma$ level with exposures as low as a few minutes, depending on the source brightness. In the soft X–ray domain the All–Sky Monitor (ASM) onboard the Rossi X–ray Timing Explorer (RXTE) can provide continuously a daily-averaged flux, while the X–Ray Telescope (XRT) onboard the Swift satellite can observe the source with far better precision and energy resolution in $\sim 1$ ks targeted exposures. From the observation of the source spectrum in both X-ray and VHE an unique set of physical parameters that describe the source can be derived within a single–zone Synchrotron Self–Compton (hereafter, SSC) model, following Tavecchio et al. (1998). Historically, SSC modeling of the SED of Mrk 421 has been already performed in the past (see e.g. Bednarek & Protheroe, 1997; the same Tavecchio et al., 1998; Maraschi et al., 1999 or the more recent Fossati et al., 2008). Lately an automated $\chi^2$ minimization procedure (Mankuzhiyil et al. 2011) has been applied.

The main limitations to previous works come from the use of the former IACTs such as Whipple, characterized by a higher energy threshold and worse sensitivity at VHE. This in turn led to poor sampling of the IC peak region, basically limited to the less
informative, steeply decaying hard energy tail of the bump; moreover, integration over different nights of observation was commonly needed to obtain a significant VHE spectrum, thus averaging out the SED evolution. Therefore most of the earlier works were based on multiwavelength, but non tightly simultaneous data, thus weakening the result for such a variable source, as in this case the X-ray and VHE telescopes perhaps sample different states and the spectra are not closely related to each other. In 2008 Mrk 421 went through a long and intense outburst phase, characterized by VHE fluxes quite constantly above the Crab level and superimposed shorter and brighter flares; a noteworthy dense follow-up of this evolution was possible in optical, X-rays and VHE with MAGIC-I. The main outcome of this campaign is that eight tightly contemporary observations of Mrk 421 in optical, X-rays and VHE γ-rays of active states could be achieved, allowing determination of the optical–UV/X-ray/TeV MWL SED of Mrk 421 in high state with unprecedented simultaneity and sensitivity. The paper is planned as follows: in Section 2 we report on the observations and data analysis; in Section 3 we report the VHE light curve and spectra, and complementary results in X-rays and optical–UV band; in Section 4 we build the SED of Mrk 421 in the eight states for which a set of multiwavelength simultaneous data was available and we model it in the framework of a standard one–zone SSC model; finally we discuss the results in Section 5.

2. Observations and data analysis

The timespan of the MAGIC VHE observations of Mrk 421 reported here starts in December 2007 and ends in June 2008. Contemporary data from other instruments are considered for the multiwavelength analysis, namely soft X–ray data from RXTE/ASM, and Swift/XRT, optical–UV data from Swift/UVOT and optical R–band data from the Tuorla Observatory. A summary description of the instruments, the datasets and the analysis follows.

2.1. MAGIC-I VHE observations

MAGIC-I (formerly MAGIC) is an Imaging Air Cerenkov Telescope (IACT) located on the western Canarian Island of La Palma, at the Observatory of Roque de los Muchachos (28.75° N, 17.89° W, 2225 m a.s.l.). With its tessellated parabolic mirror (D = 17 m, f/D = 1), it has been the largest single dish IACT in operation from late 2004 until first light of MAGIC-II in 2009, a twin (but substantially improved under many respects) telescope, with which is now operated as a stereo IACT system (MAGIC Stereo). Its 234 m² surface allowed for the lowest energy threshold amongst concurrent IACT systems: the trigger threshold of the telescope at the epoch of this campaign reached as low as 60 GeV for observations close to the zenith in optimal conditions. A detailed description of the telescope and can be found in dedicated papers (e.g. Baixeras et al. 2004, Cortina et al. 2005, Albert et al. 2008a). All the MAGIC-I observations considered for the present study are subsequent to a major hardware upgrade (Goebel et al. 2008) completed in February 2007, that enhanced (from 300 MHz to 2 GHz) the time sampling capability of the DAO. This allowed for better rejection of the Night Sky Background (NSB) and introduction of new refined analysis techniques (Tescaro et al. 2008, Aliu et al. 2009) based on the time properties of Cherenkov signals.

Along the observation period considered here, MAGIC observed Mrk 421 in a total of 81 nights, with exposure times ranging from ~ 20 to ~ 240 minutes. This comprised both short untriggered observations, aimed to an unbiased sampling of the source state (studied in detail in Aleksić et al. in preparation), and deeper extended observations of peculiar states, triggered either by the former or by external alerts from other bands. All the observations have been performed in the false–source tracking (“wobble”, Fomin et al. 1994) mode. The method consists in alternatively tracking two positions in the sky that are symmetrical with respect to the source nominal position and 0.4° far from it.

The MAGIC-I data were analyzed using the standard analysis chain described in Albert et al. (2008a, b); Aliu et al. (2009). Preliminary quality checks were performed in order to exclude poor quality data, such as those due to bad weather or occasional technical problems. Further, the dataset was restricted to observations performed under dark conditions, and in the range of zenith angle ranging from ~ 5° at culmination to 46°. A cleaning algorithm involving time structure of the shower images was then applied, further selecting the events and removing the Night Sky Background (NSB) contribution to the images. Surviving images were parametrized in terms of the extended set of Hillas parameters (Hillas 1985) described in the mentioned literature. In order to suppress the unwanted background showers produced by charged cosmic rays, a multivariate classification method known as Random Forest (RF, Breiman 2001) is implemented and applied (Albert et al. 2008b). An analogous procedure allows the estimation of the energy of the primary γ-rays. The signal extraction was performed by applying cuts in the SIZE, HADRONNESS and ALPHA parameters, described in the aforementioned literature. In particular the SIZE cut, rejecting events with less than 150 photoelectrons of total charge, implies an energy threshold ~ 140 GeV in the present analysis. A total excess of ~ 48 × 10³ events from the selected ~ 60 hours of observation was detected. The whole analysis procedure was step by step validated on compatible datasets from observations of the Crab Nebula.

2.2. Optical, UV and X–ray observations

The Swift satellite (Gehrels et al. 2004) is a NASA mission, launched in 2003, devoted to observations of fast transients, namely GRB prompt observations. These are detected with the monitoring coded mask Burst Alert Telescope (BAT, Barthelmy et al. 2005) sensitive to 15–150 keV X-rays and covering a wide Field of View (FoV) with a resolution of few arcminutes, and then rapidly targeted with the two co–aligned pointing instruments, X–Ray Telescope (XRT, Burrows et al. 2005) and Ultra–Violet Optical Telescope (UVOT, Roming et al. 2005).

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The fast repositioning capability of the spacecraft allows snapshotting of variable sources with little overheads. In the case of Mrk 421, observations lasting ~ 1 ks allow the derivation of a detailed X–Ray spectrum and multi–filter optical–UV photometry due to the sensitivity of the targeted instruments and the brightness of the source.

\textit{Swift}/XRT is a Wolter type I grazing incidence telescope, with 110 cm\(^2\) effective area, 23.6' FoV and 15” angular resolution, sensitive in the 0.2–10 keV energy band. During the MAGIC campaign the instrument performed 43 targeted X-ray observations of Mrk 421 with 1–2 ks typical exposure times. \textit{Swift}/XRT data were reduced using the software distributed with the \textsc{heasoft} 6.3.2 package by the NASA High Energy Astrophysics Archive Research Center (HEASARC). The \textit{xrtpipeline} was set for the photon counting or window timing modes and having selected single pixel events (grade 0).

UVOT is a 30 cm diffraction limited optical–UV telescope, equipped with 6 different filters, sensitive in the 1700–6500 wavelength range, in a 17' × 17' FoV. Unfortunately, during the January 2008 campaign UVOT didn’t observe the source, so that the UVOT datasets were fewer than XRT pointings and, for instance, 5 out of the 8 datasets studied in Section 4 have no contemporaneous UVOT observations. Therefore we restricted the analysis of UVOT data to the three observation simultaneous with MAGIC-I performed on February the 11th and April the 2nd and 3rd, with the UV filters alone. Analysis was performed by means of the \textit{uvotimsum} and \textit{uvotsource} tasks with a source region of 5", while the background was extracted from a source–free circular region with radius equal to 50" (it was not possible to use an annular region, because of a nearby source). The extracted magnitudes have been corrected for Galactic extinction using the values of Schlegel et al. (1998) and applying the formulae by Pe\textsc{\textregistered} (1992) for the UV filters, and eventually have been converted into fluxes following Poole et al. (2008).

The All-Sky Monitor (ASM) onboard of the \textit{Rossi} X-ray Timing Explorer (RXTE, Bradt et al. [1993]) is sensitive enough to set one point per day from Mrk 421, therefore with poorer precision but denser coverage than \textit{Swift}/XRT; the publicly available ASM data products have been taken from the results provided by the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA’s GSFC.

The Tuorla Observatory constantly monitors the MAGIC VHE (known or potential) target sources, by means of the 35 cm remotely operated KVA optical telescope also located at Roque de los Muchachos and of a 103 cm telescope located at Tuorla, Finland. Along the time span of the MAGIC-I observations, 117 observations of Mrk 421 were performed in the Johnson \textit{R} band.

3. Results

3.1. MAGIC-I VHE light curves

The night-averaged integral flux above a conservative threshold of 200 GeV was calculated for each one of the 66 nights with datasets surviving the quality cuts. The VHE light curve of Mrk 421 along the campaign is plotted in the top panel of Figure 1. It is worth noticing that even if Mrk 421 is believed to emit a low VHE flux baseline (Schubnell et al., 1996), the flux was seldom below \(F_{\gamma} \lesssim 10^{-10}\) cm\(^{-2}\)s\(^{-1}\) ( Mystery line).

The sensitivity of MAGIC-I allowed to investigate the sub–hour scale evolution of VHE flux for Mrk 421 in high state, searching for the rapid variations already reported in literature (Gaidos et al., 1996). The most interesting result was obtained on February the 6th, when a long (~ 4 hours) observation of a high (~ 2.5 C.U. above 200 GeV) state was performed. The VHE light curve in 8 minute time bins is shown in Figure 2 above a softer \((E > 200\text{ GeV})\) upper panel) and harder \((E > 400\text{ GeV})\) lower panel) energy threshold. An episode of variability with doubling/halving times down to 16 minutes can be seen with the harder cut. The hypothesis of a steady flux is unfit in both light curves according to results of a \(\chi^2\) test, giving \(\chi^2/n_d\) of 55/28 (probability below 0.2 %) and 63/28 (probability \(\sim 10^{-9}\) respectively, and confirming variability on the scale of hours or less. Unfortunately, no simultaneous Swift/XRT was performed in this period, thus it was not be included in the set of simultaneous MWL SED.

As far as the simultaneous dataset are concerned, no firm conclusion could be drawn on sub hour variability, as some observations windows were very short (e.g. April the 2nd and 3rd) other in lower flux levels (e.g. January 8, 9, 10), leading to poorer event statistics.

3.1.1. Multiwavelength data

\textit{Swift}/XRT observed count rates in the 0.2 – 10 keV band are reported in the second panel of Figure 1. The count rates observed by RXTE-ASM in the 2 – 10 keV band are shown in the middle–lower panel of Figure 1. The \textit{R}–band optical light curve from KV A observations is reported in the bottom panel of Figure 1, while the available measurements referred to the simultaneous datasets listed in Table 3 are plotted in Figure 5 after correction for Galactic extinction, again applied according to the values of Schlegel et al. (1998).

3.2. VHE spectra derived from MAGIC-I data

We restricted the study of the spectra to the subset of the eight observations of interest for the modeling of the MWL SED (see Section 4), listed in Table 3. From each observation we derived a VHE spectrum in bins of the estimated energy of the \(\gamma–\)ray primary events. Then we applied the Tikhonov unfolding algorithm (Albert et al., 2007b) in order to reconstruct the physical spectrum in...
Fig. 1. Multi-wavelength light curves of Mrk 421 along the MAGIC observation period; full circles mark the fluxes observed when MAGIC and Swift/XRT pointed simultaneously the source. Upper panel: MAGIC VHE light curve above 200 GeV, for the 66 observation nights that passed quality cuts. MAGIC detected the source clearly in all the nights; the integral flux was below the Crab Unit (C.U., $\sim F_{E>200\text{ GeV}} = 2.0 \times 10^{-10}$ photons $\text{cm}^{-2}\text{s}^{-1}$, represented here by the dashed horizontal line) only in a few nights. A maximum flux of $\sim 3.6$ C.U. has been observed on 2008 March the 30th (MJD=54555). Middle–lower panel: soft X–ray (2–10 keV) count rates measured by RXTE–ASM. Lower panel: Johnson R–band optical light curve from the Tuorla Observatory.

terms of the true energy of the primary $\gamma$–rays. A best fit to the data was then performed, assuming a log–parabolic model for the differential spectrum:

$$\frac{dN}{dE\,dA\,dt} = f_0 \times \left( \frac{E}{E_0} \right)^{a+b \log \left( \frac{E}{E_0} \right)}$$

(1)

where the pivot energy $E_0$ is chosen 300 GeV in the present case. The parameters of the fit and the $\chi^2$ are reported in Table I quoted uncertainties are statistical only. The spectral points were hereafter corrected for Extra–Galactic Background Light (EBL) absorption. The Franceschini et al. (2008) EBL model has been assumed in this work, even if consistent results can be obtained
Fig. 2. Mrk 421 VHE light curves in 8 minutes time bins, from the observations taken on 2008, February the 6th. Integral flux of excess (filled circles) and background (thin crosses) events is plotted. The Energy threshold is 200 GeV (upper panel) and 400 GeV (lower panel).

with other models such as the more recent [Domínguez et al. (2011)], given that for such a closeby source the model-to-model differences in opacity below 10 TeV are dominated by the statistical uncertainties in hour-scale integrated VHE spectra. The data points are plotted in Figure 4 along with the SSC models (see Section 4.1) that are anticipated here only as a help to guide the eye. For comparison is also plotted, without model, the SED built from the observation achieving the record VHE flux of the whole campaign (2008 March 30). Unfortunately, this dataset could not be included in the SED study, as Swift could only observe with 14 hours of delay with respect to MAGIC-I in this case. Anyway, the VHE spectrum derived from this observation is intriguingly hard, peaking around 500 GeV, well within the MAGIC-I band. In Figure 3 the observed SED (black open triangles) is plotted together with the deabsorbed one (red filled circles), that peaks above 1 TeV.

Table 1. Results of MAGIC-I VHE observations of Mrk 421 for the 8 nights with overlapping MAGIC-I and Swift-XRT data and good data quality. For each night, the integral VHE flux above 200 GeV is reported in the first column. The best fit parameters to the observed (no EBL correction) spectrum are reported, with statistical errors only. The fit function chosen is a curved power law, except for three cases where a simple power law fitted the data.
Fig. 3. VHE SED of Mrk 421 derived from the MAGIC-I observations performed on March the 30th, when the flux rose up to 3.6 Crab Units. Data points before (black open triangles) and after (red filled circles) applying a correction for EBL absorption following Franceschini et al. 2008 are shown. The observed position of the IC peak is evaluated at ~ 500 GeV from the fit with a curved power law, and above 1 TeV after deabsorption. This VHE spectrum was the hardest amongst the ones studied, as illustrated in Figure 4.

3.3. Soft X-ray spectra derived from Swift-XRT data

In the case of the eight simultaneous observations with MAGIC-I listed in Table 3 we extracted the spectra in order to build the MWL SED (see Section 4). Data were rebinned in order to have at least 30 counts per energy bin. Broken power law models have been fitted to the spectra. In Table 2 we report the spectral parameters for the observations used for modelling the SED. The X-ray reddening due to absorbing systems along the light travel path has been corrected assuming the Galactic value for column density of neutral hydrogen $N_H = 1.6 \times 10^{20}$ cm$^{-2}$ (Lockman & Savage 1995).

Table 2. Results of the best fit with a broken power law model, in the range 0.35-10 keV to the X–ray spectra of Mrk 421, obtained from the eight Swift/XRT pointings contemporary to MAGIC-I observations (see Section 4). For each dataset are reported (with uncertainties in parentheses): the Obs ID, the UTC time at the beginning of observation, the exposure time, the integral flux in the 2–10 keV band, the spectral indexes, break energy and normalization at 1 keV of the broken power law model assumed for the fit, and the resulting $\tilde{\chi}^2$/ndf.

| Obs. ID   | Start Time (UT) | $F_{2-10\text{keV}}$ erg/cm$^2$/s [10$^{-12}$] | $\alpha_1$ | $E_{\text{break}}$ keV | $\alpha_2$ | $f_0$ | $\tilde{\chi}^2$/ndf |
|-----------|-----------------|-----------------------------------------------|-------------|------------------------|------------|------|---------------------|
| 00030352041 | 20080108 02:30  | 2.0  | 280 | 2.31(0.03) | 1.20(0.09) | 2.58(0.03) | 0.242(0.003) | 1.34/163 |
| 00030352042 | 20080109 04:04  | 2.0  | 283 | 2.28(0.03) | 1.05(0.10) | 2.60(0.03) | 0.257(0.005) | 1.30/170 |
| 00030352044 | 20080110 02:27  | 2.3  | 284 | 2.32(0.02) | 1.10(0.10) | 2.57(0.02) | 0.245(0.003) | 1.59/178 |
| 00030352053 | 20080116 03:21  | 1.2  | 345 | 2.19(0.04) | 1.24(0.18) | 2.45(0.04) | 0.242(0.004) | 1.16/122 |
| 00030352055 | 20080117 03:29  | 0.8  | 311 | 2.21(0.03) | 1.97(-0.18/+0.4) | 2.75(-0.09/+0.19) | 0.243(0.003) | 1.33/101 |
| 00030352068 | 20080211 03:40  | 1.9  | 587 | 2.19(0.01) | 2.43(0.02) | 2.57(0.06) | 0.372(0.002) | 1.76/215 |
| 00030352083 | 20080402 00:42  | 0.9  | 474 | 2.09(0.02) | 2.86(0.03) | 2.51(-0.08/+0.15) | 0.260(0.003) | 1.47/130 |
| 00030352086 | 20080403 21:59  | 1.2  | 961 | 1.95(0.02) | 2.37(-0.16/+0.28) | 2.33(0.06) | 0.438(0.003) | 1.48/210 |

4. Simultaneous multi–wavelength datasets

Hereafter we focus on the 8 cases for which tightly simultaneous observations in VHE with MAGIC-I telescope and in X–rays with Swift/XRT could be performed. Table 3 summarizes the observation logs of the two instruments for these nights. It is worth noticing that the MAGIC-I data considered for each night cover always a timespan that is bigger than Swift exposures: this was necessary, as the typical observation time of Swift in this campaign (1 ks) is enough for deriving a rather detailed X–ray spectrum of Mrk 421, but the significantly lower count rate available in the γ–ray domain makes such an exposure time too short for deriving a VHE spectrum detailed enough for the modeling. Therefore for each night the whole MAGIC-I exposure was used to derive the VHE spectrum given that the observing conditions were stable and no evidence for sharp evolution of the source arose from the VHE light curves at minute scales. For each of the eight states under study, we build the MWL SED matching the MAGIC, Swift/XRT and optical–UV (either R–band from KVA, or UV from Swift/XRT, or both). As an example, the SED of Mrk 421 as observed on 2008 February the
Fig. 4. VHE SED of Mrk 421 derived from the MAGIC-I observations performed in the 8 timeslots with tightly simultaneous Swift-XRT data (see Section 4). The spectra are shown after correction of the EBL absorption, following Franceschini et al. (2008). For comparison, the spectrum derived from the observation that registered the highest flux (3.6 C.U. above 200 GeV) of the whole campaign, performed on 2008 March the 30th. For each night, our model (see Section 4.1) is plotted, to help guide the eye.

11th is plotted in Figure 5 compared to historical MWL data taken from Tavecchio & Ghisellini (2008). It is worth noticing that the VHE SED is high and hard, while the X–ray SED is high but rather soft with respect to past states where the synchrotron peak was observed at higher energies. The wide separation of the two peaks is further discussed in Section 4.1.

4.1. SED modeling

In order to reduce the degrees of freedom, we use a simple one-zone SSC model (for details see Tavecchio et al., 1998; Maraschi & Tavecchio, 2003). The emission zone is supposed to be spherical with radius R, in motion with bulk Lorentz factor $\Gamma$ at an angle $\theta$ with respect to the line of sight. Special relativistic effects are described by the relativistic Doppler factor, $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$. The energy distribution of the relativistic emitting electrons is described by a smoothed broken power law function, written for better clarity in terms of the adimensional Lorentz parameter $\gamma = E/m_e c^2$; the distribution spans the [$\gamma_{\text{min}}, \gamma_{\text{max}}$] energy range, with slopes $n_1$ and $n_2$ below and above the break energy $\gamma_b$, respectively.

To calculate the SSC emission we use the full Klein–Nishina cross section (Jones, 1968).
| Night     | MAGIC Obs.        | Swift/XRT Obs. | Overlap |
|-----------|-------------------|----------------|---------|
|           | Start (UT) Time   |                |         |
|           | (hh:mm)           | (ks)          |         |
| 20080108  | 01.58 02.44       | 02.30 2.0     | 0.8     |
| 20080109  | 03.56 06.19       | 04.04 2.0     | 2.0     |
| 20080110  | 02.23 06.05       | 02.27 2.3     | 1.1     |
| 20080116  | 03.17 05.11       | 03.21 1.2     | 1.2     |
| 20080117  | 03.26 04.25       | 03.29 0.8     | 0.8     |
| 20080211  | 03.33 03.58       | 03.40 1.9     | 1.1     |
| 20080402  | 00.45 01.00       | 00.42 0.9     | 0.6     |
| 20080403  | 21.55 22.20       | 21.59 1.2     | 1.1     |

Table 3. Summary of the 8 tightly simultaneous observations of Mrk 421 with MAGIC-I and Swift/XRT. For each night, the beginning (col. 1) and the end (col. 2) of the MAGIC-I observation timespan, the total effective time (col. 3) and the ZA range (col. 4) of each observation are reported. The start time (col. 5) and duration (col. 6) of the corresponding Swift/XRT pointing are also reported, and the truly overlapped observed time in ks (col. 7).

As detailed in Bednarek & Protheroe (1997) and Tavecchio et al. (1998), this simple model can be fully constrained by using simultaneous multiwavelength observations. Indeed, the total number of free parameter of the model is reduced to 9: the 6 parameter specifying the electron energy distribution plus the Doppler factor, the size of the emission region and the magnetic field. On the other hand, from X–ray and VHE observations ideally one can derive 7 observational quantities: the slopes of the synchrotron bump before and above the peak $\alpha_{1,2}$ (uniquely connected to $n_{1,2}$), the synchrotron and SSC peak frequencies ($\nu_{s,C}$) and luminosities $L_{s,C}$ and the minimum variability timescale $t_{\text{var}}$, which provides an upper limit to the size of the sources through the relation $R < c t_{\text{var}} \delta$. It must be noted that, as long as $\gamma_{\text{min}} \ll \gamma_b \ll \gamma_{\text{max}}$ the values of $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ are not much constrained by the observation of the peaks. Nevertheless, the availability of the spectral shape across the instrument bandpasses and of data at other wavelengths (optical and UV in this case) provide additional constraints with respect to the simple 7 quantities enumerated above. Therefore, once all the observational quantities are known, one can unambiguously derive the set of parameters. In this respect, the cases studied here...
are rather favorable, since we have a rather good determination of the peak frequencies (and fluxes) of both peaks. Indeed, although the synchrotron peak of Mrk 421 is seldom observed within the band encompassed by XRT, the joint optical–UV and X–ray data provide a good constraint to the position of the synchrotron peak in all the cases. The SSC peak is located either within (see e.g. the SED from Figure 11 in Figure 5) the MAGIC-I band, or around its lower edge; in the latter case the pronounced curvature of the MAGIC-I spectrum at the lowest energies allows to constrain the peak at energies not much below \( \approx 50 \text{ GeV} \).

Unfortunately for the epochs used to derive the SEDs we do not have information on the variability timescale, \( t_{\text{var}} \), one of the key observational parameters needed to completely close the system and uniquely derive the parameters. In the X–ray band Swift/XRT observed in short (\( \sim 1 \) ks) snapshots, while no pressing evidence for sub–hour variability arose from the corresponding MAGIC-I observations. Therefore we still have some freedom in choosing the input parameters: one can obtain different sets of parameters, reproducing the spectral data equally well but differing in the predicted observed minimum variability timescale.

We have applied the model to all the eight sets of data collected when \( \text{Swift} \) and MAGIC-I could observe simultaneously the source. UVOT and \( K\alpha \) data were also included in the SED when available. The sets of parameters obtained from the modeling are reported in Table 4 and the SED data and the corresponding model are plotted in Figure 6. We note that in reproducing the SED we do not consider the radio data, since the modeled region is opaque at these frequencies: in this framework the radio emission originates in regions of the jet farther away from the black hole, beyond the core visible at VLBI scale, thought to mark the radio “photosphere”. Accordingly, the inferred source radius is well within the upper limit of \( 0.1 \) pc \((3 \times 10^{17} \text{ cm})\) imposed by Charlot et al. (2006) for the projected size of the SSC zone, based on VLBI observations of the radio core.

Inspection of Table 4 shows that the derived Doppler factors are rather large, exceeding \( \delta = 40 \) in all the cases and reaching values as large as \( 80-85 \) in the most extreme cases. The main reason for such large values of \( \delta \) is the large separation between the two peaks, the synchrotron one located below \( 10^{37} \) Hz, the SSC one around \( 10^{23} \) Hz or above. As detailed in e.g. Tavecchio & Ghisellini (2008) a large distance between the two peaks implies a rather large value of the Lorentz factor at the peak, \( \gamma_b \), since \( \gamma_b = (\gamma_C/\gamma_n)^{1/2} \), and this directly implies a low \( B \) and a large \( \delta \) to satisfy the other constraints.

However we recall that, since the variability timescale is not known, we are left with some freedom in selecting the input parameters. In the models reported in Figure 6 we assume variability timescales in the range \( 0.5–2 \) hours, as typically derived for these sources (see Discussion below). In general, the required Doppler factor roughly scales with the observed variability timescale as \( \delta \propto t_{\text{var}}^{-0.5} \) (e.g. Tavecchio & Ghisellini 2008). Therefore, relaxing the condition on \( t_{\text{var}} \) allowing longer minimum variability timescales one gets lower \( \delta \). As an example we use the case for which we derive the largest \( \delta \), that of February 11, requiring \( \delta = 85 \). As noted above this is a case in which the determination of the peak frequencies is very robust, since the SSC peak falls well within the band covered by MAGIC-I. Therefore this is also the best “benchmark” available to test the robustness of the derived parameters. For this purpose we modeled this SED assuming two sets of parameters, basically differing for the value of the Doppler factor, the radius of the emitting region and the magnetic field intensity. For the case assuming \( \delta \approx 85 \) we have \( t_{\text{var}} = 0.7 \) h \((2.5 \times 10^5 \text{ s})\), while more than halving the Doppler factor \( \delta = 40 \) implies a rather long variability timescale, \( t_{\text{var}} = 5 \) h \((1.8 \times 10^4 \text{ s})\), already larger than the characteristic variability timescale of Mrk 421 in the X–ray band. We can conclude that for the case of February 11, although the parameters cannot be uniquely fixed, the required Doppler factor is large, at least larger than \( \delta = 40 \). All the other cases are similar. The derived light crossing times range in the \( 0.5–2 \) hours interval. This hypothesis matches well the observed typical rising/decaying timescales of flares of Mrk 421 and similar HBLs (PKS 2155-304, Mrk 501), characterized by doubling/halving times of \( \approx 10^4 \) s (e.g. Fossati et al. 2008, Ruvasio et al. 2004, Zhang 2002, Tanihata et al. 2000), with evidences for the occurrence of even faster events (e.g. Gaidos et al. 1996, Cui 2004).

However, relaxing this assumption on the variability timescale the required Doppler factors remains large. In the case of the observations of February 11, which allows us to firmly constrain the synchrotron and SSC peak, this implies \( \delta > 45 \).

It is worth being pointed out that, following for instance the formulae in Bednarek & Protheroe (1997) or Tavecchio et al. (1998), rather large cooling times \( t_{\text{cool}} \), of the order \( 10^5 \) s in the observer’s frame, can be computed from the model parameters in Table 4.

Therefore, adiabatic expansion, that allows quenching of the flux within scales of \( R/c \) has to be invoked as one of the viable processes that may explain the observed descent of TeV and X–ray fluxes on hour scales. But it must be noted that such an explanation has the significant drawback of implying a very energetically inefficient jet. This issue could therefore hint to the unsuitability of the one–zone model for this source. In the spine–layer structured model, for instance, in general a 10 times larger \( B \) can be adopted.

### Table 4. Input model parameters for the eight nights with tightly simultaneous MAGIC-I and \( \text{Swift}/ \)XRT data. For each night the minimum, break and maximum Lorentz factors of the electron distribution, the low and high energy slopes of the electron distribution, the magnetic field and the electron density within the emitting region, the radius of the emitting region, its Doppler factor and the resulting light crossing time are reported.

| Night | \( \gamma_{\text{min}} \) | \( \gamma_{b} \) | \( \gamma_{\text{max}} \) | \( n_1 \) | \( n_2 \) | \( B \) | \( K \) | \( R \) | \( \delta \) | \( t_{\text{var}} \) |
|-------|----------------|----------------|----------------|--------|--------|--------|--------|--------|--------|--------|
| 20080108 | 7.0 | 6.0 | 3.0 | 2.0 | 4.0 | 5.0 | 1.70 | 9.0 | 45 | 1.8 |
| 20080109 | 10 | 2.9 | 3.0 | 2.0 | 4.0 | 4.3 | 3.70 | 5.0 | 85 | 0.5 |
| 20080110 | 6.0 | 5.7 | 3.0 | 2.0 | 4.0 | 3.7 | 3.30 | 5.0 | 70 | 0.7 |
| 20080116 | 8.3 | 6.7 | 3.0 | 2.0 | 4.0 | 2.5 | 4.00 | 5.0 | 80 | 0.6 |
| 20080117 | 10 | 6.0 | 0.7 | 2.0 | 4.2 | 3.7 | 2.60 | 7.2 | 60 | 1.1 |
| 20080211 | 11 | 6.9 | 3.0 | 2.0 | 3.7 | 2.0 | 2.40 | 6.6 | 85 | 0.7 |
| 20080402 | 8.0 | 3.2 | 1.0 | 2.0 | 3.5 | 5.0 | 5.90 | 3.9 | 70 | 0.5 |
| 20080403 | 17 | 20 | 3.0 | 2.0 | 4.0 | 4.0 | 2.00 | 8.5 | 40 | 2.0 |
when modeling a given SED (see e.g. Ghisellini et al. 2005); as the synchrotron cooling time scales as $t_{\text{sync}} \propto B^{-2}$, this could lead to cooling times of the order of the needed variability time scale.

5. Discussion

During the 2008 campaign on Mrk 421 with MAGIC-I a very interesting dataset was gathered in VHE $\gamma$-rays, complemented by crucial data in optical–UV and soft X–rays. For the first time it was possible to collect data in these bands in close simultaneity during high states of the source, so that the derived spectra sampled the SED close to the synchro and IC peaks. In this situation the parameters describing the source in the framework of the standard one-zone leptonic model can be determined with unprecedented robustness. One of the most relevant results of our analysis is that, in order to reproduce the observed SED with this model, very large Doppler factors are required. There is some freedom in choosing the parameters, mainly due to the not known variability timescale at those epochs. In the models summarized in Table 3 and reported in Figure 6 we assume variability timescales in the range 0.5–2 hours.
Actually, such large values of inferred $\delta$ are not rare: very large Doppler factors, sometimes larger than $\delta \sim 50$, for Mrk 421 and other well observed HBLs were obtained in the past, leading to the so called “$\delta$-crisis” (e.g. Krawczynski et al. 2002, Konopelko et al. 2003, Georganopoulos & Kazanas 2003). Analogously, the recent exceptional VHE flare of PKS 2155-304 (Aharonian et al. 2007) seems to require extreme Doppler factors in the framework of one-zone models (Begelman et al. 2008, Ghisellini & Tavecchio 2008 Finke et al. 2008, Kusunose & Takahara 2006). Such large values of $\delta$ (implying similarly large value of the bulk Lorentz factors) contrast with the very small jet velocities inferred at VLBI scales in this a large fraction of TeV BL Lacs (e.g. Girolotti et al. 2004, Piner & Edwards 2004), including Mrk 421, and with the value of $\Gamma$ required from the unification of BL Lacs and FRI radioagalaxies (e.g. Urry & Padovani 1995).

Georganopoulos & Kazanas (2003) and Ghisellini et al. (2005) propose a solution to this problem based on the possibility that the flow is characterized by portions moving at different speeds. If these regions emit, in each of them the electrons can scatter not only the locally-produced synchrotron photons, but also the soft photons produced in the other region. Moreover, the energy density of these “external” photons is amplified in the rest frame of the emitting region due to the relative speed between the two portions of the flow. The result is that the inverse Compton emission of each region is amplified with respect to the SSC emission. As a consequence, the Doppler factor required to reproduce the SED is lower than those of the one-zone model. In particular, in the “spine-layer” model of Ghisellini et al. (2005), it is assumed that the jet has a inner faster core (the spine) surrounded by a slower layer. At small angle of view, those characterizing blazars, the emission is dominated by the faster spine whose IC emission is a mixture of SSC and “external” Compton components. Such a model would also accomodate more easily the short variability time scales observed in Mrk 421, that within the one–zone model are hardly explained due to the long electron cooling times, as discussed in Section 4.1

A modeling of the SED with the more complex (and less constrained) structured-jet model is beyond the scope of this paper and left to future work.

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