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MAGIC DISCOVERY OF VERY HIGH ENERGY EMISSION FROM THE FSRQ PKS 1222+21

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ABSTRACT

Very high energy (VHE) γ-ray emission from the flat spectrum radio quasar (FSRQ) PKS 1222+21 (4C 21.35, $z = 0.432$) was detected with the MAGIC Cherenkov telescopes during a short observation (~0.5 hr) performed on 2010 June 17. The MAGIC detection coincides with high-energy MeV/GeV γ-ray activity measured by the Large Area Telescope (LAT) on board the *Fermi* satellite. The VHE spectrum measured by MAGIC extends from about 70 GeV up to at least 400 GeV and can be well described by a power-law $dN/dE \propto E^{-\Gamma}$ with a photon index $\Gamma = 3.75 \pm 0.27_{\text{stat}} \pm 0.2_{\text{syst}}$. The averaged integral flux above 100 GeV is $(4.6 \pm 0.5) \times 10^{-10}$ cm^{-2} s^{-1} (~1 Crab Nebula flux). The VHE flux measured by MAGIC varies significantly within the 30 minute exposure implying a flux doubling time of about 10 minutes. The VHE and MeV/GeV spectra, corrected for the absorption by the extragalactic background light (EBL), can be described by a single power law with photon index 2.72 ± 0.34 between 3 GeV and 400 GeV, and is consistent with emission belonging to a single component in the jet. The absence of a spectral cutoff constrains the γ-ray emission region to lie outside the broad-line region, which would otherwise absorb the VHE γ-rays. Together with the detected fast variability, this challenges present emission models from jets in FSRQs. Moreover, the combined *Fermi*/LAT and MAGIC spectral data yield constraints on the density of the EBL in the UV–optical to near-infrared range that are compatible with recent models.

Key words: cosmic background radiation – galaxies: active – galaxies: jets – gamma rays: galaxies – quasars: individual (PKS 1222+21)

1. INTRODUCTION

High-luminosity active galactic nuclei (AGNs) hosting powerful relativistic jets are characterized by strong nonthermal emission extending across the entire electromagnetic spectrum, from radio up to γ-rays. More than 40 AGNs have been detected in the very high energy (VHE) domain ($E > 100$ GeV) by ground-based Cherenkov telescopes.[32] The great majority of them are BL Lac objects, while only two are classified as flat spectrum radio quasars (FSRQs): PKS 1510−08 ($z = 0.36$; Wagner & Behera 2010) and 3C 279 ($z = 0.536$; Albert et al. 2008; Aleksic et al. 2011b), the most distant VHE source detected up to now.

FSRQs display luminous, broad emission lines often accompanied by a "big blue bump" in the optical–UV region, associated with the direct emission from the accretion disk. VHE emission from FSRQs may therefore be affected by internal absorption from the dense UV–optical radiation reprocessed in the broad-line region (BLR; Donea & Protheroe 2003). Distant VHE quasars offer the possibility to probe the extragalactic background light (EBL), the integrated stellar and dust emission through cosmic history, in the range 0.1–10 μm (Hauser & Dwek 2001).

The MAGIC detection (Mariotti et al. 2010) of the FSRQ PKS 1222+21 (4C 21.35, $z = 0.432$; Osterbrock & Pogge 1987) makes it the second most distant object with known redshift (after 3C 279) detected at VHE.[33] PKS 1222+21 is a γ-ray blazar (Abdo et al. 2010b) with a relatively hard spectrum in the GeV range and has been included in the list of >100 GeV emitters in the analysis of Neronov et al. (2010). It is characterized by highly superluminal jet knots with apparent velocity up to 21c (Lister et al. 2009).

Upper limits on the VHE emission of PKS 1222+21 have been previously derived by Whipple (Kerrick et al. 1995) at the level of 12×10^{-12} cm^{-2} s^{-1} at $E > 300$ GeV. We report here on the MAGIC discovery of this source, during a phase of high activity in γ-rays announced by the *Fermi*/LAT Collaboration. We discuss its implications for the EBL studies and the blazar physics.

2. OBSERVATIONS

MAGIC consists of two 17 m diameter Imaging Atmospheric Cherenkov Telescopes located at the Roque de los Muchachos, Canary Island of La Palma (28°46′ N, 17°53′ W), at the height of 2200 m a.s.l. The stereo observations provide a sensitivity[34] of 0.8% of the Crab Nebula flux at $E > 250$ GeV (Colin et al. 2009).

PKS 1222+21 was observed by MAGIC from 2010 May 3 to June 19 (MJD 55319 to MJD 55366) for a total of ∼14.3 hr. The observations started as a part of a Target of Opportunity program triggered by an increase of the flux in the *Fermi* passband (Donato 2010). In this Letter, we report the results obtained from the observation of June 17 (MJD 55364), when the source was detected by MAGIC in close coincidence with the brightest flare observed by the *Fermi* Large Area Telescope (LAT; Tanaka et al. 2011). Results from the multi-wavelength campaign covering all 2010 observations will be published elsewhere. Nevertheless, a preliminary analysis does not provide any high-significant detection with MAGIC in any other day during the campaign.

On June 17, 21:50 UT, PKS 1222+21 was observed with the MAGIC telescopes for ∼0.5 hr (MJD 55364.908 to MJD 55364.931), in the so-called wobble mode. The data were taken at zenith angles between 26° and 35°. The light conditions during the observations correspond to moderate moon light leading to a higher noise level in the data. A cleaning level higher than the standard one was therefore applied to remove signals from night sky background noise. Stereoscopic events, triggered by both MAGIC telescopes, were analyzed in the MARS analysis framework (Moralejo et al. 2009). Details on the analysis can be found in Aleksic et al. (2011a) whereas the performance of the MAGIC telescope stereo system will be discussed in detail in a forthcoming paper.

3. RESULTS

The strength of the signal was evaluated applying standard cuts to the PKS 1222+21 data sample, corresponding to an energy threshold of ≈70 GeV as determined by Monte Carlo events, assuming a soft spectrum with a photon index of $\Gamma = 3.5$. The θ^2 distribution (squared angular distance between the true and reconstructed source position) of the signal coming from the region of PKS 1222+21 yields an excess of 190 γ-like events (6 γ minute^{-1}), corresponding to a statistical significance of 10.2σ using Equation (17) in Li & Ma (1983).

3.1. VHE Spectrum

The differential energy spectrum of PKS 1222+21 was reconstructed using the "Tikhonov" unfolding algorithm (Albert et al. 2007), to take into account the finite energy resolution of the instrument and the biases in the energy reconstruction. The energy spectrum, shown in Figure 1, extends up to at least 400 GeV and is well described by a simple power law of the form

$$\frac{dN}{dE} = N_{200} \left(\frac{E}{200\ \mathrm{GeV}} \right)^{-\Gamma} \quad (1)$$

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[32] For an updated list refer to http://tevcat.uchicago.edu/ or http://www.mppmu.mpg.de/∼rwagner/sources/

[33] The redshift measurement ($z = 0.444$) of the VHE BL Lac 3C 66A has large uncertainties (Bramel et al. 2005).

[34] Sensitivity is defined here as the minimal integral flux to reach 5σ signal in 50 hr of observations.

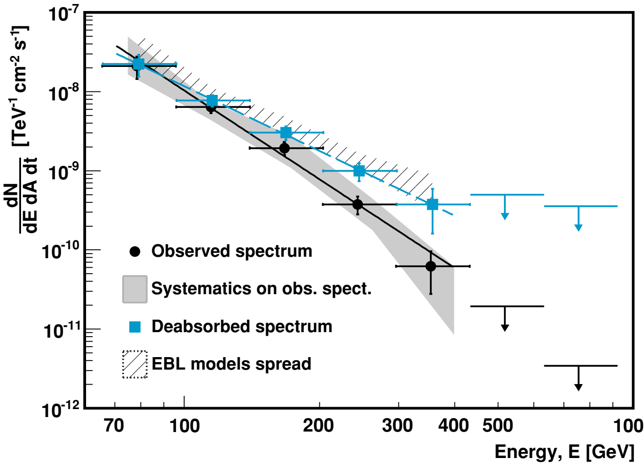

Figure 1. Differential energy spectrum of PKS 1222+21 as measured by MAGIC on 2010 June 17. Differential fluxes are shown as black points, upper limits (95% CL) as black arrows. The black line is the best fit to a power law. The gray shaded area represents the systematic uncertainties of the analysis. The absorption corrected spectrum and upper limits using the EBL model by Dominguez et al. (2011) are shown by the blue squares and arrows; the dashed blue line is the best-fit power law. The blue-striped area illustrates the uncertainties due to differences in the EBL models cited in the text, by Kneiske & Dole (2010), Gilmore et al. (2009), Franceschini et al. (2008), and Albert et al. (2008).

with a photon index $\Gamma = 3.75 \pm 0.27_{\rm stat} \pm 0.2_{\rm syst}$ and a normalization constant at 200 GeV of $N_{200} = (7.8 \pm 1.2_{\rm stat} \pm 3.5_{\rm syst}) \times 10^{-10}$ cm^{-2} s^{-1} TeV^{-1}, yielding an integral flux $(4.6 \pm 0.5) \times 10^{-10}$ cm^{-2} s^{-1} (≈1 Crab Nebula flux) at $E > 100$ GeV and $(9.0 \pm 3.6) \times 10^{-12}$ cm^{-2} s^{-1} (7% of the Crab Nebula flux) at $E > 300$ GeV, at the same level of Whipple upper limit (Section 1). For energies higher than 400 GeV no significant excess was measured. The upper limits corresponding to 95% confidence level (CL) are shown in Figure 1. The systematic uncertainty of the analysis (studied by using different cuts and different unfolding algorithms) is shown by the gray area.

We studied the effect of the VHE γ-ray absorption due to pair production with low energy photons of the EBL by using different state-of-the-art EBL models, namely, the models by Dominguez et al. (2011), Kneiske & Dole (2010), Gilmore et al. (2009), Franceschini et al. (2008), and the “max high UV” EBL model described in Albert et al. (2008). For each of the EBL models, the optical depth corresponding to the measured VHE γ-ray energy intervals was computed and the differential fluxes were corrected accordingly to obtain the de-absorbed (or intrinsic) spectrum. The spectrum deabsorbed with the EBL model of Dominguez et al. (2011), shown by the blue squares in Figure 1, is well fitted by a power law with an intrinsic photon index of $\Gamma_{\rm intr} = 2.72 \pm 0.34$ between 70 GeV and 400 GeV. Uncertainties caused by the differences between the EBL models are represented in Figure 1 by the blue-striped area. The corresponding spread is smaller than the systematic uncertainties of the MAGIC data analysis.

We investigated the possible presence of a high-energy (HE) cutoff in the VHE range by fitting power laws with different photon indexes and different values for the cutoff. The method adopted is the χ^2 difference method (see, e.g., Lampton et al. 1976). With the available statistics, at the 95% CL we cannot exclude the presence of a cutoff above 130 GeV for a photon index 2.4 (the lowest possible value compatible with fit uncertainties and with *Fermi*/LAT data, see Section 3.3) or above 180 GeV for a photon index 2.7. The confidence interval is not bounded on the HE side, i.e., a fit without a cutoff is fully compatible with the data. Further observations with higher statistics are needed to better constrain the location of a possible steepening in the form of a cutoff or spectral break.

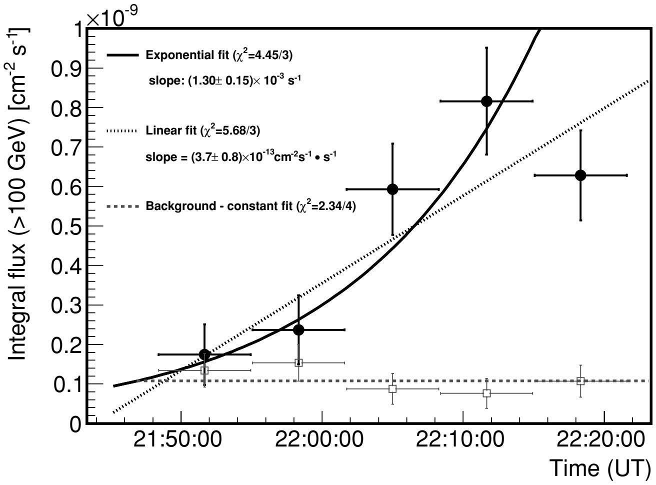

Figure 2. PKS 1222+21 light curve above 100 GeV, in 6 minutes bins (black filled circles). The observation was carried out on MJD 55364. The black solid line is a fit with an exponential function and the black dotted line a fit with a linear function. The gray open squares denote the fluxes from the background events and the gray dashed line is a fit with a constant function to these points.

3.2. *Light Curve*

Despite the short observation time, the strength of the signal allows us to perform a variability study of the measured integral fluxes above 100 GeV. The light curve binned in 6 minutes long intervals is shown in Figure 2 and reveals clear flux variations. The constancy hypothesis ($\chi^2/\mathrm{NDF} = 28.3/4$) is rejected with high confidence (probability $< 1.1 \times 10^{-5}$). The fluxes of background events surviving the γ/hadron selection cuts are compatible with being constant, and hence we can exclude a variation of the instrument performance during the observation.

To quantify the variability timescale we performed an exponential fit (solid black line in Figure 2). A linear fit is also acceptable but does not allow us to define a timescale unambiguously. For the exponential fit the doubling time of the flare is estimated as $8.6^{+1.1}_{-0.9}$ minutes. The derived timescale corresponds to the fastest time variation ever observed in an FSRQ in the VHE range and in any other energy range (Foschini et al. 2011), and is among the shortest timescales measured on TeV emitting sources (Abramowski et al. 2010).

3.3. *The HE–VHE SED*

In the HE MeV/GeV energy range measured by *Fermi*/LAT the source showed a significant flare lasting ∼3 days, with a flux peak on 2010 June 18 (MJD 55365) (Tanaka et al. 2011). A dedicated analysis found that the 1/2 hr MAGIC observation fell within a gap in the LAT exposure, thus we analyzed a period of 2.5 hr (MJD 55364.867 to 55364.973), encompassing the MAGIC observation. The LAT analysis for this time bin was performed as in Tanaka et al. (2011), where details can be found. It results in an integral flux $(6.5 \pm 1.9) \times 10^{-6}$ cm^{-2} s^{-1} at energy $E > 100$ MeV. The observation in such a short time does not provide any detection with *Fermi*/LAT at $E > 2$ GeV. Two *Fermi*/LAT spectral points up to 2 GeV together with an upper limit at the 95% CL in the range 2–6.3 GeV are combined

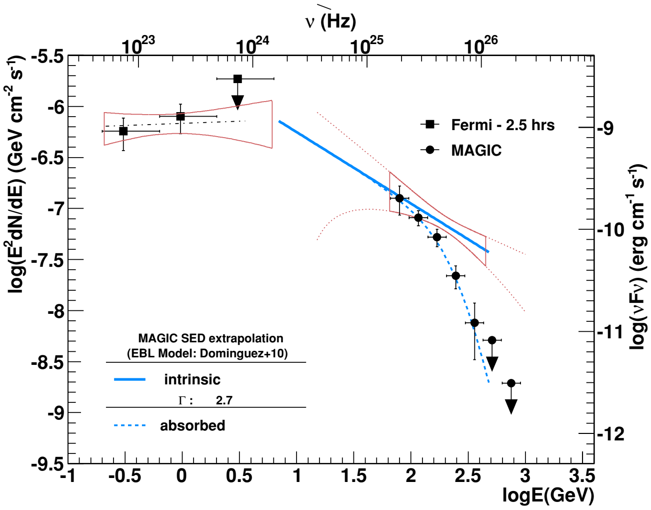

Figure 3. High-energy SED of PKS 1222+21 during the flare of 2010 June 17 (MJD 55364.9), showing *Fermi*/LAT (squares) and MAGIC (circles) differential fluxes. A red bow tie in the MeV/GeV range represents the uncertainty of the likelihood fit to the *Fermi*/LAT data. The unfolded and deabsorbed spectral fit of the MAGIC data is also shown as a red bow tie, extrapolated to lower and higher energies (dotted lines) according to Abdo et al. (2009). A thick solid line (photon index $\Gamma = 2.7$) indicates a possible extrapolation of the MAGIC deabsorbed data to lower energies. The thick dashed line represents the EBL absorbed spectrum obtained from the extrapolated intrinsic spectrum using the model by Dominguez et al. (2011).

with the MAGIC data in the spectral energy distribution (SED) shown in Figure 3.

The figure also shows bow ties representing uncertainties associated with the spectral fits. The *Fermi*/LAT spectrum is best described by a single power law with index of 1.95 ± 0.21. In the case of MAGIC data the bow tie refers to the "intrinsic" source spectrum, i.e., to the observed spectrum corrected for EBL absorption, described in Section 3.1. An extrapolation of the intrinsic spectrum in the MAGIC range to lower energies is also shown indicating that: (1) there is a potentially smooth connection between the *Fermi*/LAT and MAGIC extrapolated data in the 3 to 10 GeV region and (2) the photon index steepens from 1.9 in the *Fermi*/LAT range to 2.7 in the MAGIC range. These results agree with the analysis of wider temporal intervals during this flare and during the whole active period, in which the source spectrum is well described by a broken power law with an energy break falling between 1 and 3 GeV (Tanaka et al. 2011). Furthermore, it is found that the HE tail ($E > 2$ GeV) of the *Fermi*/LAT spectrum of PKS 1222+21 extends up to 50 GeV, with a photon index in the range 2.4–2.8.

4. DISCUSSION

4.1. *EBL Limits*

The interaction of VHE γ-rays with low energy photons of the isotropic EBL is a process with an energy dependent threshold, thus leading to an imprint of the EBL density on the measured VHE γ-ray spectra of extragalactic sources (Mazin & Raue 2007). For PKS 1222+21 ($z = 0.432$), the measured spectrum spans from 70 GeV to 400 GeV probing EBL photons in the range 0.1–1 μm (i.e., UV to near-infrared).

The EBL constraints using VHE γ-rays are usually derived assuming an intrinsic spectrum of the source (e.g., Aharonian et al. 2006). In FSRQs, the presence of dense radiation fields of soft photons can lead to the internal absorption of VHE γ-rays, mimicking harder-than-intrinsic spectra (e.g., Sitarek & Bednarek 2008). However, for realistic spectral distributions of the internal photon fields it should not change the EBL limits significantly (Tavecchio & Mazin 2009).

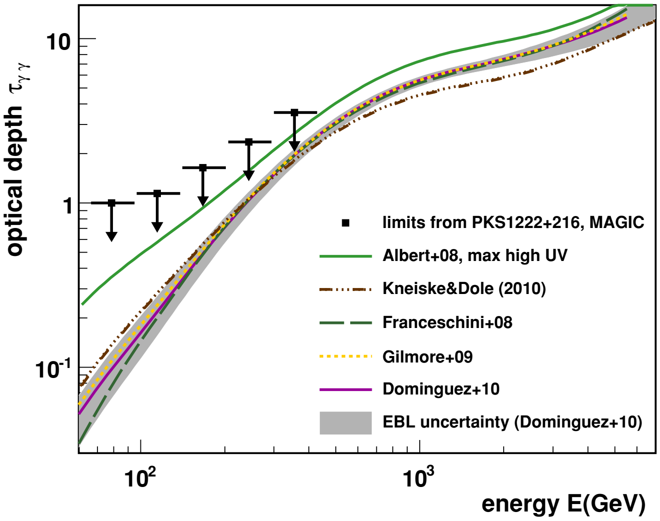

Figure 4. Optical depth along the line of sight to PKS 1222+21 ($z = 0.432$) for a range of EBL models and the limits (95% CL) from the MAGIC measurement, assuming the limiting intrinsic photon index $\Gamma_{\mathrm{VHE}} = 2.4$. The gray shaded area shows the uncertainties in the EBL determination as derived in Dominguez et al. (2011), Section 6.1 and Figure 13.

In our case the simultaneous data from *Fermi*/LAT, which is free from internal or external absorptions, have been used to constrain the intrinsic photon index in VHE (e.g., Georganopoulos et al. 2010; Finke & Razzaque 2009). We adopt a method similar to the one utilized by Georganopoulos et al. (2010): the intrinsic spectrum in the VHE regime is assumed to follow the extrapolation of the *Fermi*/LAT above 3 GeV with a $\Gamma = 2.4$. This is a conservative assumption since in reality the spectrum could soften with increasing energy.

The upper limit (95% CL) on the optical depth, $\tau_{\max}$, for VHE γ-rays can be obtained from

$$\tau_{\max}(E) = \log\left[\frac{F_{\mathrm{intr}}(E)}{F_{\mathrm{obs}}(E) - 1.64 \cdot \Delta F(E)}\right], \qquad (2)$$

where $F_{\mathrm{intr}}(E)$ is the maximum intrinsic flux at energy E, and $F_{\mathrm{obs}}(E)$ and $\Delta F(E)$ are the MAGIC measured flux and its error, respectively. The maximum intrinsic flux has been normalized at 70 GeV assuming the EBL model giving a maximum flux absorption of 30% (Albert et al. 2008). The derived limits on the optical depth are shown in Figure 4 together with a compilation of the predicted optical depths for a source at $z = 0.432$ computed according to recent EBL models. The limits confirm previous constraints on the EBL models in the UV to near-infrared regimes derived using VHE (Aharonian et al. 2006; Mazin & Raue 2007; Albert et al. 2008) and HE spectra (Abdo et al. 2010a). Given the fact that the EBL models predict for this redshift a stronger absorption with increasing energy, our data do not indicate a softening of the spectrum within the energy range of our observations.

4.2. *VHE γ-ray Emission*

In the framework of the currently accepted EBL models, the observed simultaneous VHE and GeV spectra are consistent with a single power law with index $\sim 2.7 \pm 0.3$ between 3 GeV and 400 GeV, without a strong intrinsic cutoff. This evidence suggests that the 100 MeV–400 GeV emission belongs to a unique component, peaking at ≈2–3 GeV, produced in a single region of the jet. If the emission process is inverse Compton (IC) scattering on external photons by relativistic electrons in the jet, as commonly assumed, a strong softening of the spectrum is expected above few tens of GeV if the external photons derive from the BLR. This is due to the combination of two effects: the decreased efficiency of the IC scattering occurring in the Klein–Nishina (KN) regime (e.g., Ghisellini & Tavecchio 2009) and the absorption of γ-rays through pair production (Reimer 2007; Tavecchio & Mazin 2009; Liu & Bai 2006).[35]

The energy above which the KN effects become important can be roughly expressed as $E_{\rm KN} \simeq 22.5\,\nu_{o,15}^{-1}$ GeV, where $\nu_{o,15}$ is the frequency of the target photons in units of 10^{15} Hz (or $E_{\rm KN} \simeq 75\,\lambda_{\mu\rm m}$ GeV in wavelength μm units). γ-ray absorption becomes effective when $E_{\gamma\gamma} \simeq 60\,\nu_{o,15}^{-1}$ GeV ($E_{\gamma\gamma} \simeq 200\,\lambda_{\mu\rm m}$ GeV). Above this energy a cutoff is then expected. The importance of both effects in the 10–100 GeV band is reduced if the external photon field is associated with the IR torus ($\nu_{\rm o} = 10^{13}$ Hz), as envisioned by the "far dissipation" scenarios (e.g., Sikora et al. 2008). In that case both effects start to be important above ≈1 TeV. The absence of a spectral break or cutoff in the spectrum observed by MAGIC strongly suggests that the γ-ray emission is not produced within the BLR.

The other important result of the MAGIC observation is the evidence of fast variability, $t_{\rm var} \sim 10$ minutes, indicating an extremely compact emission region with transverse dimensions, $R \sim 1.3 \times 10^{14}(\delta/10)(t_{\rm var}/10\ \text{minutes})$ cm. This seems to be difficult to reconcile with the "far dissipation" scenarios if the emission takes place in the entire cross section of the jet (see also Tavecchio et al. 2010). Estimating the size of the BLR, $R_{\rm BLR}$ from the accretion disk luminosity, $L_{\rm disk} = 5 \times 10^{45}$ erg s^{-1} (Fan et al. 2006), the distance of the emitting region is expected to be around $d > R_{\rm BLR} = 3 \times 10^{17}$ cm. Assuming a conical jet with constant opening angle $\theta_{\rm j}$ (see, however, the suggestion of recollimation; Marscher 1980), its size would be $R \sim \theta_{\rm j} d \sim 3 \times 10^{16}(\theta_{\rm j}/5^\circ)$ cm. The absence of absorption features in the VHE spectrum allows also to exclude absorption within the emitting region and, together with the observed variability, to put a lower limit to the Doppler factor of the source. From Dondi & Ghisellini (1995), Equation (3.7), assuming a power-law photon index 1.5 for the spectrum of the optical target photons, we get a lower limit $\delta > 15$, in agreement with Doppler factors derived from radio observations (Section 1).

A possibility to reconcile the spectral information (pointing to emission beyond the BLR) and the fast variability is to invoke the presence of very compact emission regions embedded within the large-scale jet, as already proposed by several authors to explain the exceptionally rapid variability in PKS 2155−304, Mkn 501, and AO 0235+164 (Ghisellini & Tavecchio 2008; Giannios et al. 2009; Marscher & Jorstad 2010). An alternative possibility is that the jet experiences a strong recollimation forming a small emitting nozzle (e.g., Nalewajko & Sikora 2009) as already suggested for M87 and PKS 2155−304 (e.g., Bromberg & Levinson 2009; Stawarz et al. 2006). Alternative scenarios involving proton-driven cascades or proton-synchrotron emission in amplified magnetic fields, e.g., generated by filamentation instabilities (Frederiksen et al. 2010), could also play a role.

In conclusion, the MAGIC observations of VHE emission from the FSRQ PKS 1222+21 put severe constraints on emission models of blazar jets. These results were obtained from a short observation of a flaring source thanks to the collaboration between the MAGIC and *Fermi* projects. Repeated and hopefully longer observations of flaring blazars with MAGIC and *Fermi* promise substantial progress in the study of extreme blazars.

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[35] We note that this absorption has been invoked by Poutanen & Stern (2010) to explain the existence of an apparently "universal" break energy in the γ-ray spectrum of FSRQs at 2 GeV.

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