Constraints given by the MAGIC discovery of the Flat Spectrum Radio Quasar PKS1222+21 in VHE Gamma rays

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Abstract. The MAGIC telescopes discovered very high energy (VHE, E > 100 GeV) gamma-ray emission coming from the distant Flat Spectrum Radio Quasar (FSRQ) PKS 1222+21 (4C +21.35, z = 0.432). It is the second most distant VHE gamma-ray source, with well measured redshift, detected until now. The observation was performed on 2010 June 17 (MJD 55364.9) using the two 17 m diameter imaging Cherenkov telescopes on La Palma (Canary Islands, Spain). The MAGIC detection coincides with high energy MeV/GeV gamma-ray activity measured by the Large Area Telescope (LAT) on board the Fermi satellite. The averaged integral flux above 100 GeV is equivalent to 1 Crab Nebula flux. The VHE flux measured by MAGIC varies significantly within the 30 minutes of 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, can be described by a single power law with photon index 2.72 ± 0.34 between 3 GeV and 400 GeV, consistent with gamma-ray emission belonging to a single component in the jet. The absence of a spectral cut-off constrains the gamma-ray emission region to lie outside the broad line region, which would otherwise absorb the VHE gamma-rays. Together with the detected fast variability, this challenges present emission models from jets in FSRQs.

1. Introduction

Flat Spectrum Radio Quasars (FSRQs) are blazars which present broad emission lines often accompanied by a ‘big blue bump’ in the optical-UV region, associated with the thermal emission from the accretion disk. Only two FSRQs had been detected in Very High Energy (VHE) γ-rays, 3c279 [1] and PKS1510-089 [2]. The detection of the FSRQ PKS 1222+21 (4C +21.35, z = 0.432,[3]) by MAGIC makes it the second most distant object with known redshift (after 3C 279, the most distant VHE source detected until now, z = 0.536 [1, 4]) ever detected at VHE1.

In this proceeding, we present the MAGIC discovery of this source in the VHE [5], which was detected during a gamma-ray flare announced by the Fermi/LAT collaboration, and its physics implications.

1 The redshift measurement (z = 0.444) of the VHE BL Lac 3C 66A has large uncertainties [6].
2. MAGIC observations

MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) consists of two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACT) 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. MAGIC observed PKS 1222+21 from 2010 May 3, but the source was not detected until June 17, 2010 (MJD 55364). The observation carried out on June 17 lasted 30 minutes and was performed as part of a Target of Opportunity program triggered by an increased flux in the Fermi energy band [7]. During this detection by MAGIC the source was close to the brightest flare ever observed by the Fermi Large Area Telescope (LAT) [8]. The data were taken at zenith angles between 26° and 35°. Stereoscopic events, triggered by both telescopes, were analyzed in the MARS analysis framework [9]. Details on the analysis can be found in [10] whereas the performance of the MAGIC telescopes stereo system will be discussed in detail in a forthcoming paper [11].

The signal evaluation was performed using the $\theta^2$ distribution (squared angular distance between the true and reconstructed source position), see the Figure 1. We got an excess of 190 $\gamma$-like events (6 $\gamma$/min.) above a background of 86 events, which corresponds to a statistical significance of 10.2 $\sigma$ using eq. 17 in [12]. The energy threshold of this analysis is $\approx 70$ GeV.

![Figure 1](image.png)

Figure 1. Distribution of the squared angular distance ($\theta^2$) for events in the direction of PKS 1222+21 (black points) and normalized off-source events (gray histogram). The signal is extracted in the $\theta^2$-region denoted by the vertical dashed line.

3. The Very High Energy Spectrum

The differential energy spectrum of PKS 1222+21 measured by MAGIC extends from 70 GeV to 400 GeV (Figure 2), and it is well-described by a simple power law of the form:

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

with a photon index $\Gamma = 3.75 \pm 0.27_{\text{stat}} \pm 0.2_{\text{syst}}$ and a normalization constant at 200 GeV of $N_{200} = (7.8 \pm 1.2_{\text{stat}} \pm 3.5_{\text{syst}}) \times 10^{-10} \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}$, yielding an integral flux $(4.6 \pm 0.5) \times 10^{-10} \text{cm}^{-2}\text{s}^{-1}$ ($\approx 1$ Crab Nebula flux) at $E > 100$ GeV. For energies higher than
400 GeV, no significant excess was found but two upper limits corresponding to 95% confidence level (C.L.) have been derived. The method used for the spectral reconstruction is the so-called “Tikhonov” unfolding algorithm [17], which takes into account the finite energy resolution of the instrument and the biases in the energy reconstruction. The systematic uncertainty of the analysis (studied by using different cuts and different unfolding algorithms) is shown by the gray area.

To derive the intrinsic spectrum emitted at the source the VHE spectral data is de-absorbed using the EBL model described in [13] (Fig. 2 blue points). It is well fitted by a power law with an intrinsic photon index of $\Gamma_{\text{intr}} = 2.72 \pm 0.34$ between 70 GeV and 400 GeV. Uncertainties caused by the differences between the EBL models are investigate utilizing different EBL models [13, 14, 15, 16, 1]. The corresponding spread (Fig. 2 blue shaded area) is smaller than the systematic uncertainties of the MAGIC data analysis.

The possibility of a cut-off in the energy spectrum was studied using the $\chi^2$ difference method. Fitting the spectrum with a broken power law with different photon indexes and values for the cut-off, we cannot exclude the presence of a cut-off above 130 GeV for a photon index 2.4 (the lowest possible value compatible with fit uncertainties and with the Fermi/LAT data) or above 180 GeV for a photon index 2.7, with the available statistics.

4. The Spectral Energy Distribution

The high-energy Spectral Energy Distribution (SED) is shown in Figure 3 where the MeV/GeV energy range spectrum from Fermi/LAT and the GeV/TeV spectrum measured by MAGIC are represented. The source showed a significant flare in the Fermi band lasting $\sim$3 days, with a peak flux on 2010 June 18 (MJD 55365) [8]. During the 1/2 hr MAGIC observation there is

**Figure 2.** 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% C.L.) 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 of [13] 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 of [14, 15, 16] and [1].
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). 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 of [13].

A gap in the LAT exposure, so we analyzed the closest data available, a period of 2.5 hr (MJD 55364.867 to 55364.973) centered around the MAGIC observation. Given the short observation time (chosen in order to be as much contemporaneous as possible with the MAGIC data) there is no detection above 2 GeV in the Fermi/LAT data, but an upper limit at the 95% C.L. in the energy range $2 - 6.3\text{ GeV}$ has been calculated together with the spectral points up to 2 GeV (details on the analysis can be found in [8]) and combined with the MAGIC data in the SED shown in Fig. 3.

Extrapolating the intrinsic MAGIC spectrum to lower energies we can see that there is a potentially smooth connection between the Fermi/LAT and MAGIC extrapolated data and the photon index steepens from 1.9 in the Fermi/LAT range to 2.7 in the MAGIC range. These results agree with the results from the analysis of Fermi-LAT data of larger 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 between 1 and 3 GeV [8]. Furthermore it is found that the high energy tail ($E > 2\text{ GeV}$) 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.

5. Source Variability

Due to the strength of the signal, even if the observation time is as short as 30 minutes, a variability study is possible. In Fig. 4, the MAGIC VHE light curve binned in 6 minutes long intervals is shown. It reveals a flux variation within the 30 minutes of observation time. The hypothesis of a constant flux is rejected ($\chi^2/\text{NDF} = 28.3/4$) with high confidence (probability $< 1.1 \times 10^{-5}$). The flux of the background events surviving the $\gamma$/hadron selection cuts
is compatible with being constant and hence we can exclude a variation of the instrument performance during the observation.

To quantify the variability time scale, we performed an exponential fit (solid black line in Fig. 4). A linear fit is also acceptable but does not allow us to define a time scale unambiguously. For the exponential fit the doubling time of the flare is estimated to $8.6^{+1.1}_{-0.9}$ 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 [21], and is amongst the shortest measured from any TeV emitting source [22, 23].

6. Conclusions

As discussed, the almost simultaneous VHE and GeV spectra are consistent with a single power law with index $\sim 2.7 \pm 0.3$ between 3 GeV to 400 GeV, without a strong intrinsic cut-off. This evidence suggests that the 100 MeV - 400 GeV emission belongs to a unique component, peaking at $\approx 2 - 3$ GeV, produced in a single region of the jet. Considering the inverse Compton scattering on external photons and relativistic electrons in the jet as the emission process, as it is usually assumed, we have two possible scenarios. The emitting jet region could be inside of the Broad Line Region (BLR), where the external photons field would be the UV photons from the BLR, or we can assume this emitting region to be outside of the BLR, where the photon field would be composed of the IR photons coming from the torus. There are two important effects that need to be taken into account: the decreased efficiency of the IC scattering occurring in the Klein-Nishina (KN) regime and the absorption of $\gamma$-rays through pair production.

The energy above which the KN effects and $\gamma$-ray absorption become important in the case of UV external photons from the BLR is $\sim$ tens of GeV, and thus we would expect a cut-off at these energies, if the emitting jet region is inside the BLR. But if we consider as target photons the ones coming from the IR torus this effect is expected to appear at much higher energies.
above $\approx 1$ TeV, because this effect depends on the frequency of the external target photons. Since there is no evidences of a cut-off at low energies we can conclude that the emission should come from outside of the BLR, as has been proposed by the “far dissipation” scenarios (e.g. [20]).

Besides, the other important result of the MAGIC observation is the fast variability, $t_{\text{var}} \sim 10$ minutes which indicates an extremely compact emission region. Fast variability suggests that the emission takes place close to the black hole and thus inside of the BLR.

Some explanations have been already proposed, in order to explain this kind of observational facts, invoking the presence of very compact emission regions embedded within the large scale jet [24], turbulent cell model [25] or the possibility of a very strong jet recollimation (e.g. [18]).

In conclusion, the MAGIC observations of VHE emission from the FSRQ PKS 1222+21 set severe constraints on the emission models of blazar jets.

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[1] J. Albert et al., Science, 2008, 320, 1752
[2] S. Wagner & B. Behera, 10th HEAD Meeting, BAAS, 42, 2, 07.05
[3] D. E. Osterbrock & R. W. Pogge, ApJ, 1987, 323, 108
[4] J. Aleksic et al., A&A, 2011, 530, A4
[5] J. Aleksic et al., ApJL, 2011, 730, L8
[6] D. A. Bramel, ApJ (2005), 629, 108
[7] D. Donato, The Astronomer’s Telegram, #2584
[8] Y.T. Taniaka, ApJ, 2011, 733 (1), 19
[9] A. Moralejo et al., Proc. of 31st ICRC, 2009, [arXiv:0907.0943]
[10] J. Aleksic et al., ApJL, 2010, 726, 58, [arxiv:1010.0550]
[11] J. Aleksic et al., in prep.
[12] T.-P. Li & Y.-Q. Ma, ApJ, 1983, 272, 317
[13] A. Dominguez et al., MNRAS, 2011, 410, 2556
[14] T. M. Kneiske & H. Dole, A&A, 2010, 515, 19
[15] R. Gilmore et al., MNRAS, 2009, 399, 1694
[16] A. Franceschini et al., A&A, 2008, 487, 837
[17] J. Albert et al., Nucl. Instr. Meth., 2007, A 583, 494
[18] K. Nalewajko & M. Sikora, MNRAS, 2009, 392, 1205
[19] G. Ghisellini & F. Tavecchio, MNRAS, 2008, 386, 28
[20] M. Sikora et al., ApJ, 2008, 675, 71
[21] L. Foschini et al., A&A, 2011, 530, A77
[22] A. Franceschini et al., ApJ, 2007, 664, L71
[23] J. Albert et al., ApJ, 2007, 663, 125
[24] F. Tavecchio et al., Submitted to A&A, 2011, [arXiv:1104.0048v1]
[25] A. P. Marscher and S. G. Jorstad, 2010, [arXiv:1005.5551]