FERMI view of the TeV blazar Markarian 421

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***Abstract*. The high energy component of the TeV blazar Markarian 421 has been extensively studied since the beginning of the 90s, when the source was first detected at gamma-rays with EGRET and the Whipple Telescope, yet the source is still far from being understood. The high sensitivity, large dynamic range, and excellent time coverage of the Fermi Large Area Telescope (LAT), all representing significant advances over previous gamma-ray observations, will play a key role in the elucidation of the physical processes underlying the high energy emission of this blazar. In this presentation we show the results from almost 6 months (4 August 2008 to 20 January 2009) of observation with LAT. We report significant flux/spectral variability on a range of time scales from weeks to days, and an energy spectrum from 0.1 GeV to 300 GeV, overlapping with the energy ranges covered by the current generation of Cherenkov Telescopes.**

***Keywords*: Spectral Analysis, Gamma-Rays, Galaxies**

I. INTRODUCTION

Blazars are a type of AGN where a jet of plasma, moving at relativistic speed, is pointing close to the line of sight of the observer. Most of the identified extragalactic sources detected with EGRET belong to this category [3]. Although blazars have been observed for tens of years now, the existing experimental data does not allow one to unambiguously identify the physical mechanisms responsible for the electromagnetic emission. Given the existing high sensitivity detectors to study the low energy component (radio, IR, optical and X-rays), one of the main reasons for this lack of understanding was the low instrumental sensitivity at energies between 0.5 MeV and 0.3 TeV. This poor sensitivity often precluded detailed cross-correlation studies between low and high energy emission and leads to a big inter-model and intra-model degeneracy. More and higher quality data at gamma-ray energies are required for a better understanding of these objects. This applies particularly to data corresponding to the *low state* of the blazars, where the previous instruments were not sensitive enough to obtain significant detections in reasonably short times. Some of the still open and very fundamental questions are: the particle content of the jets (leptons/hadrons), the location and size of the acceleration/emission zone(s), the nature of the processes producing flares with timescales down to minutes, the role of external photon fields, and the effect of the Extragalactic Background Light (EBL) attenuation on the observed spectra.

The Large Area Telescope (LAT) instrument, on board of the Fermi satellite (in scientific operation since August 2008) is expected to shed light on blazar phenomenon. In this manuscript we report on the Fermi view of the TeV High-frequency Peaked BL Lac (HBL) object Markarian 421 (Mrk421), which is one of the brightest sources in the extragalactic X-ray/TeV sky. It was actually the first extragalactic object to be discovered as TeV emitter [1], and one of the fastest varying γ-ray sources [2]. Even though this blazar is very bright at γ-ray, the knowledge we have is very incomplete (and rather biased to the high activity) due to the poor source coverage and, specially, the almost inexistent information at GeV energies. We want to point out that 9 years of operation with EGRET only resulted in a few viewing periods with a signal significance of barely 5 sigmas for Mrk421 [3]. Because of the smaller collection area, and the self-veto problem, the sensitivity of EGRET to detect high energy gammas was about 2 orders of magnitude lower than that of Fermi-LAT. Besides, during the EGRET times the sensitivity of previous generation Imaging Atmospheric Cherenkov Telescopes (IACTs) was rather poor, and they essentially operated above 0.3 TeV. Note that in only 3 months of operation, Fermi detected with high confidence 10 HBL sources, which are about half of the known TeV extragalactic sources [4] . This shows the big potential of Fermi-LAT to study this type of objects.

In the next sections we report the flux/spectral variability and the overall source spectrum from 100 MeV to 300 GeV, overlapping with the energies covered by Cherenkov Telescopes. A more extended study of Mrk421 with these Fermi data will be reported in a forthcoming publication [5].

II. DATA SELECTION AND ANALYSIS

The data selected for the analysis of Mrk421 cover the period from 4 August 2008 to 20 January 2009. The data after 20 January 2009 will be reported elsewhere in the framework of a long multi-frequency campaign organized by the Fermi AGN group [6].

During this time Fermi operated in survey mode, which means that the source was continuously observed. The analysis was performed with the diffuse class photon events (P6_V3 IRF) [7]. The flux/spectral variability was studied only above 200 MeV. Below 200 MeV, the collection area of LAT for the diffuse class photon events drops very quickly and thus larger systematics are expected due to possible uncertainties in the detector efficiency in this energy range.

One of the most important characteristics of LAT is the 8.6 radiation lenght calorimeter which provides LAT with the capability of performing spectral measurements of γ-ray sources over a large dynamic range. We report here on the results of the spectral analysis performed with the standard method provided by the Fermi Science tools. This method uses the standard LAT analysis software, *Science Tools v9r11* and performs a maximum likelihood fit of the model parameters. The source model includes a point source for Mrk421, a component for the Galactic diffuse emission along the plane of the Milky Way derived using the GALPROP code [8] and an isotropic power law component to represent the extragalactic diffuse emission. Both diffuse components are fit with the data (over a region of interest of 10 deg radius around the location of Mrk421) and hence take into account also the residual instrumental background.

III. Flux and Spectral Variability

The γ-ray flux measured by Fermi-LAT above 200 MeV is reported in Fig. 1. The data spans the time from 4 August 2008 to 20 January 2009, when the instrument operated in survey mode. The figure also shows the X-ray flux (2-12 keV) measured by RXTE/ASM since 1 January 2008. Mrk421 was found in a very active state (at X-rays and also very high energy gamma-rays) during April and June 2008, yet since July 2008 it remained in a rather low state. Despite the low source activity, the LAT instrument was capable of significantly resolving the γ-ray flux from the source (typically more than 10 sigmas) on every single week of observation.

At this point, we want to stress the remarkable improvement with respect to the other currently operating γ-ray detector, AGILE, which could only get a marginal detection with Test Statistic (TS) $\sim$20 ($\sim$4.5 σ) after one week of pointing observation during the flaring episode that occurred in June 2008 [9] and provided fluxes of about 3 times larger than the ones observed by Fermi-LAT.

The high sensitivity of the LAT instrument permitted the determination of flux and spectral shape of the gamma-ray activity of Mrk421 on time scales as short as 2 days, which is the sampling frequency for optical, X-ray and Very High Energy gamma-ray observations during the multi-frequency campaign organized by the

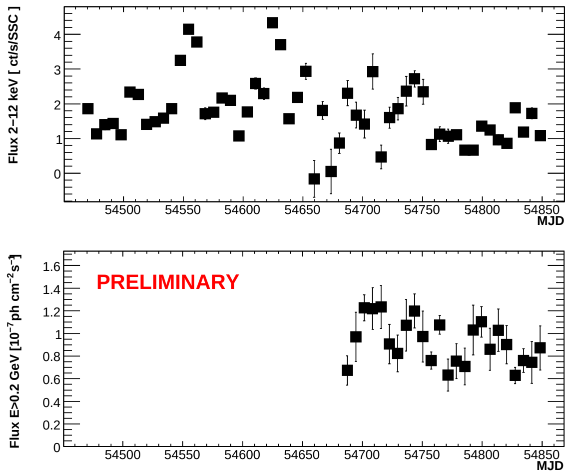

Fig. 1: Light curves from Mrk421 with weekly time bins since 1 January 2008 obtained with two all-sky-monitoring instruments: RXTE/ASM (2-12 keV, top figure), and Fermi-LAT (at E>0.2 GeV, bottom). Vertical bars denote 1 σ uncertainties.

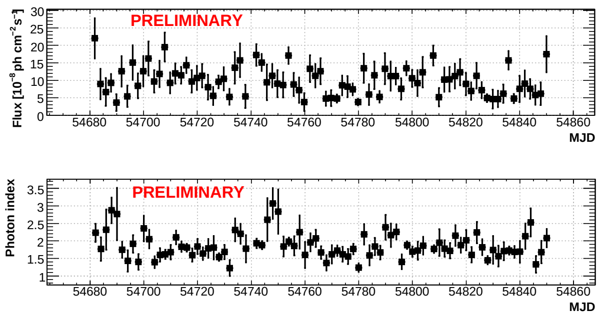

Fig. 2: γ-ray flux at E>0.2 GeV (top) and spectral photon index from a Power Law fit (bottom) from Mrk421 for 2-day time bins from 4 August 2008 to 20 January 2009. Vertical bars denote 1σ uncertainties.

Fermi AGN group, which started on 20 January 2009 and will last 5 months [6]. The measured γ-ray flux (E>0.2 GeV) and the photon index from a Power Law (PL) fit are shown on Fig. 2 for 2-day time intervals. Out of the 85 2-day time intervals covering the time window from 4 August 2008 to 20 January 2009, the source was detected on 79 (93%) 2-day time intervals above 3 sigmas, and 62 (73%) above 5 sigmas, which is very remarkable achievement given the fact that the source is in a rather low state.

The results mentioned above demonstrate the Fermi-LAT performance to study γ-ray sources. The capability to resolve flux/spectral variations at GeV energies on short timescales provides very valuable information to constrain currently available theoretical emission models. For instance, when using a particular Synchrotron-Self-Compton (SSC) model adjusted to describe various X-ray and TeV observations, typically we have several predictions for the fluxes at GeV frequencies. If we had simultaneous GeV observations with Fermi we would be able to constrain the emission model. That shows a clear case of the importance of Fermi data for the understanding of the physical processes occuring in this object, and blazars in general.

We followed the description given in [10] to quantify the flux variability by means of the fractional variability parameter F_{var}, as a function of energy. In order to account for the individual flux measurement errors ($\sigma_{err,i}$), we used the 'excess variance' [11], [12] as an estimator of the intrinsic source variance. This is the variance after subtracting the expected contribution from measurement errors. For a given energy range the F_{var} is calculated as

$$F_{var} = \sqrt{\frac{S^2 - <\sigma_{err}^2>}{<F_\gamma>^2}}$$

where $<F_\gamma>$ is the mean photon flux, S the standard deviation of the N flux points, and $<\sigma_{err}^2>$ the average mean square error, all determined for a given energy bin.

When applying this formalism to the data shown in Fig. 2, we find that the variability is 0.22 +/- 0.05 for the flux ($E > 0.2\ GeV$) and 0.12 +/- 0.02 for the photon index. Hence the source showed both flux and spectral variations during these 5.5 months of relatively low activity.

On the other hand, Fig. 3 shows the derived F_{var} values for 3 logarithmic energy bins, from 0.2 GeV to 20 GeV, when the data is split on week time bins. The first energy bin (logE[MeV]=2.3-2.8) showed a negative excess variance ($<\sigma_{\rm err}^2>$ larger than S^2), which can happen when there is little variability and/or the errors are slightly overestimated. Essentially such a result can be interpreted as no signature for variability in the lowest energy bin either because a) there was no variability or b) the instrument/analysis performance was not sensitive enough to detect it. In this particular case, upper limits of 95% confidence level were computed and displayed by means of an arrow in the figure. The plot, on the other hand, shows significant variability in the energy bins logE[MeV]=2.8-3.3 and logE[MeV] $>$ 3.3; and it suggests that the variability increases with the energy.

In the framework of leptonic models (like SSC), the variability observed in the γ-ray emission brings information about the dynamics of the underlying population of relativistic electrons (and possibly positrons). In this context, the general variability trend reported in Fig. 3 suggests that γ-ray flux variations are produced by more energetic particles, that are characterized by shorter cooling timescales; causing the higher variability amplitude observed at the highest energies.

IV. Spectrum Analysis up to 300 GeV

The overall spectral energy distribution (SED) in the energy range 0.1-300 GeV measured with Fermi-LAT is shown in Fig. 4. The black line is the result of a fit with a single PL function over the entire energy range, and the red contour is the 68% uncertainty of

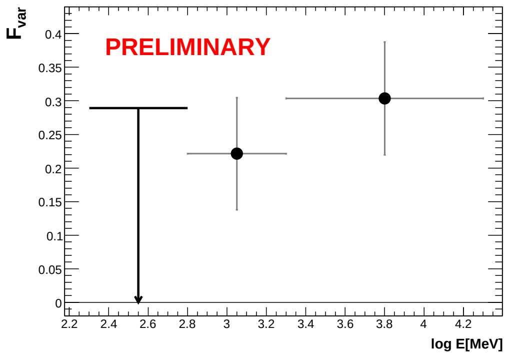

Fig. 3: Fractional variability parameter as derived for 3 energy bins according to [10]. The variability was computed using the fluxes on week time scales. Vertical bars denote 1σ uncertainties, horizontal bars indicate the width of each energy bin. The arrow indicates 95% confidence level upper limits on the fractional variability.

fit. This was performed with the standard analysis tools described in section 2. The data are consistent with a pure PL function with photon index of 1.79 +/- 0.03. The black data points are the result of performing the standard analysis (see section 2) on differential energy ranges ($log\Delta E = 0.3$)[1]. Note that the points are well within 1-2σ away from the fit to the overall spectrum (black line).

These results have been compared with an analysis performed using an unfolding technique [13], [14] based on Bayes' theorem, that permits the reconstruction of the energy spectrum of the source from the observed data after background subtraction, without assuming any parametric model, and including the energy dispersion effect of the instrument response. The results obtained are in perfect agreement (both overall spectrum and differential energy range) with the standard analysis tools.

Therefore, 3 different methods (2 of them completely independent) provided consistent results over this wide energy range.

Fig. 4 shows also the results of observations from TeV Cherenkov telescopes taken during different periods of times from 2001 to 2005. Data points were taken from [15] and show the intrinsic (EBL-corrected) source spectrum. It is worth emphasizing that those objects are varying sources that often change spectral shape and energy output by orders of magnitude. MAGIC results (pink data points) were taken during a low state of the source in 2004-2005, that showed relatively similar low X-ray flux as the one observed during the Fermi observations. With big caveats, one might try to consider the SED from Fermi and the one from MAGIC as being representative of the same state of the source. This clearly suggests a turn over of the spectrum somewhere

[1]Because of the analysis being carried out in small energy ranges, we decided to fix the spectral index to 1.79 which is the value obtained when fitting the entire energy range.

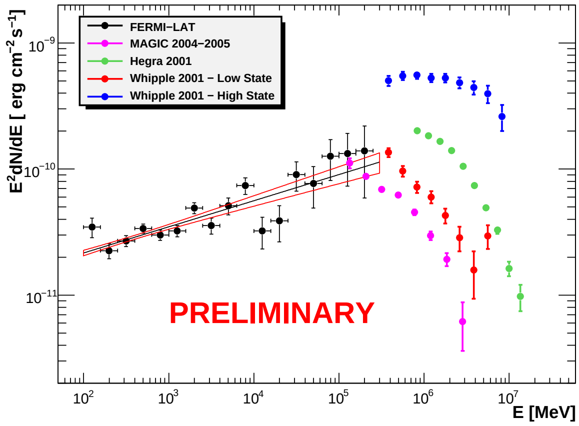

Fig. 4: Spectral energy distribution of the MRK421. Black line is the likelihood PL fit; red contour is 68% uncertainty of the fit; data points: (black) Fermi-LAT data; TeV observations: Whipple in a high state (blue) and low state (red) of the source during 2001, Hegra in 2001 (green) and MAGIC in 2004-2005 (pink).

around 100 GeV. Note that, at the energies around 100 GeV, the energy bins in Fermi data points have large statistical error bars and could hide the curvature in the spectrum. The SED measured by Fermi is actually rather consistent with a single bump expected from the SSC model.

The location of the peak at 100 GeV (it could vary with the activity level of Mrk421) is at the upper end of the energy region covered by Fermi (especially if the measurement is done in ∼week timescales), while it is at the lower end of the energy range of IACTs. Instead of a problem, that is a marvellous opportunity to study the high energy bump of this object. The coordinated observation of Mrk421 with Fermi-LAT and IACTs (covering 6 decades in energy: 20 MeV-20 TeV) can precisely resolve the rising and falling part of the high energy emission of HBLs; with the peak of the bump in the "overlapping" energy range of these two instruments. It is worth mentioning that the spectrum can be resolved with both instruments on timescales of weeks down to few days, which is expected to bring key data for the understanding of Mrk421, and blazars in general. In particular, the overall high energy bump of Mrk421 will be deeply covered (together with lower energies) in the multi-frequency campaign organized by the Fermi AGN group that started on 20 January 2009 and will last 5 months [6].

V. CONCLUSIONS

Results on the observations of the BLLac object Markarian 421 collected in the first months of operation of the Fermi satellite have been presented. Light curves on weekly and daily timescales have been shown, as well as the results of the spectral analysis in the energy range between 100 MeV and 300 GeV, covered for the first time by a satellite experiment overlapping the lower energy observations from Cherenkov telescopes on earth. These results are still preliminary and will be enriched and completed soon by a forthcoming publication [5]. The results shown here demonstrate the great performance of Fermi-LAT to study the gamma-emission from Mrk421 (and blazars in general) over a large dynamic range and also on short timescales, which is expected to be of key importance for the study of the emission of the source in a coordinated way with other instruments covering other energy ranges.

VI. ACKNOWLEDGEMENTS

We want to thank Daniel Mazin for providing us with several TeV historical spectra from Mrk421. The Fermi-LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy for science analysis during the operations phase is also gratefully acknowledged.

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