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Cut-off characterisation of energy spectra of bright fermi sources: Current instrument limits and future possibilities

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ABSTRACT

In this paper some of the brightest GeV sources observed by the *Fermi*-LAT were analysed, focusing on their spectral cut-off region. The sources chosen for this investigation were the brightest blazar flares of 3C 454.3 and 3C 279 and the Vela pulsar with a reanalysis with the latest *Fermi*-LAT software. For the study of the spectral cut-off we first explored the Vela pulsar spectrum, whose statistics in the time interval of the 3FGL catalog allowed strong constraints to be obtained on the parameters. We subsequently performed a new analysis of the flaring blazar SEDs. For these sources we obtained constraints on the cut-off parameters under the assumption that their underlying spectral distribution is described by a power-law with a stretched exponential cut-off. We then highlighted the significant potential improvements on such constraints by observations with next generation ground based Cherenkov telescopes, represented in our study by the Cherenkov Telescope Array (CTA). Adopting currently available simulations for this future observatory, we demonstrate the considerable improvement in cut-off constraints achievable by observations with this new instrument when compared with that achievable by satellite observations.

1. Introduction

The gamma-ray emission from a broad range of both galactic and extragalactic objects has revealed a multitude of effective particle accelerators. The gamma-ray energy spectrum of this emission can typically be described by a power-law distribution with a high energy cut-off, whose description we can generally encapsulate by a function of the form:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left[-\left(\frac{E}{E_c}\right)^{\beta_\gamma}\right] \tag{1.1}$$

where E_0 indicates the energy scale of the power-law region[1]; Γ represents the power-law index of the particles, E_c characterizes the position of the cut-off energy, while the parameter β_γ determines the steepness of the cut-off (stretched for $\beta_\gamma < 1$, compressed for $\beta_\gamma > 1$). The determination of these parameters from the observational data is the focus of this work.

The importance of determining the shape of the cut-off region in the gamma-ray spectrum is directly connected with the cut-off region of the primary particles. A modified exponential cut-off for these parent particles naturally arises from the interplay between acceleration and energy loss rate. To avoid confusion we will call β_γ and β_e the cut-off parameters for photons and primary particles respectively.

When considering the acceleration of particles in the Bohm diffusion regime, for scenarios in which radiative losses can be safely neglected, we would naturally expect a simple exponential cut-off, with $\beta_e = 1$. However, considering instead the acceleration of particles up to high energies for which radiative losses can no longer be ignored, the situation is more complicated. In the framework of diffusive shock acceleration [33] solved analytically the transport equation for electrons when dealing with Bohm diffusion and synchrotron losses, obtaining $\beta_e = 2$.

In the case of stochastic acceleration, already Schlickeiser [31] and Aharonian et al. [8] demonstrated the formation of modified cut-offs in the particle spectrum when balancing acceleration and radiative losses. In this context, writing the momentum diffusion coefficient as $D(p) \propto p^q$, and the energy dependence of the time scale of the radiative losses as $\tau_{cool} \propto E^r$, the resulting cut-off of the primary particles can be described by $\beta_e = 2 - q - r$ [32].

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[1] In the fitting of the *Fermi*-LAT data this parameter has been fixed to the value reported in the 3FGL catalogue [4].

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Table 1
Sources and type of event analysed. In the last column is reported the MJD interval from which the SED has been extracted.

Object	Class	Event type	Analysed period	MJD interval
3C 454.3	AGN (FSRQ)	Flare	Nov. 2010	55,516–55,523
3C 279	AGN (FSRQ)	Flare	June 2015	57,187–57,190
Vela PSR[2]	Pulsar	Avg. emission	Aug. 4, 2008–July 31, 2012	54,682–56,139

Typical values for the q parameter are: $q = 1$ for the Bohm case, $q = \frac{3}{2}$ and $q = \frac{5}{3}$ for, respectively, a Kraichnan or a Kolmogorov spectrum, and $q = 2$ for the "hard-sphere" approximation. Applied to the specific case of Bohm diffusion ($q = 1$) and synchrotron losses ($r = -1$), we obtain a $\beta_e = 2$. Thus, once again, the inclusion of synchrotron cooling in the acceleration process can lead to a sharpening of the cut-off shape.

The effect of β_e is to modify the cut-off of the primary particles, and consequently the resultant cut-off in the photon spectrum emitted. This emitted spectrum may itself be described by a stretched cut-off, with stretching parameter β_γ. For the specific case of synchrotron emission, this parameter β_γ, relates to the parent population parameter through the relation $\beta_\gamma = \frac{\beta_e}{\beta_e+2}$ [16], indicating that a cut-off in the photon spectrum with a compressed exponential shape is incompatible with a synchrotron origin and acceleration taking place in the Bohm regime where we would expect $\beta_\gamma = 0.5$.

When we deal instead with inverse Compton processes, the emitted spectrum of the scattered photons is affected by both the electron distribution and the target photon field. The outcome is also affected by the cross section of the interaction, with the resultant spectrum depending on whether the process occurred: in the Thomson regime ($\varepsilon_e \varepsilon_\gamma^{bg} \ll (m_e c^2)^2$) or Klein–Nishina ($\varepsilon_e \varepsilon_\gamma^{bg} \gtrsim (m_e c^2)^2$) regime. Analysis of the various processes has been carried out by Lefa et al. [25] taking into account different photon fields. They showed that in the Klein–Nishina regime, due to the fact that the electron loses almost all of its energy in a single interaction with the photon, the spectrum of the latter resembles the spectrum of the parent electrons, with $\beta_\gamma = \beta_e$. In the Thomson regime, instead, the photon spectrum is always stretched with $\beta_\gamma < \beta_e$. For example in the case of Inverse Compton on a Planckian photon seed field $\beta_\gamma = \frac{\beta_e}{\beta_e+2}$, while when considering a Synchrotron Self Compton mechanism, the gamma-ray photon spectrum will have a cut-off described by $\beta_\gamma = \frac{\beta_e}{\beta_e+4}$.

Another important channel for the production of gamma rays is proton-proton interactions where the gamma rays are emitted through the production and decay of secondary neutral mesons (mainly π and η). Once the description for emissivity of the π^0-meson is taken into account, it is possible to show also here that a stretching of the cut-off in the photon spectrum also occurs [20,21].

Objects for which this cut-off sits in the GeV domain, presently may be most effectively probed by the Large Area Telescope (LAT) onboard the *Fermi* satellite. This is a pair conversion telescope capable of reconstructing the direction of incoming photons with energies between 20 MeV and more than 300 GeV [10]. Unfortunately the measurement of the spectrum in the cutoff regime requires large photon statistics and this is available only for a limited number of Fermi sources.

In Section 2 a subset of some of the brightest objects observed by the *Fermi*-LAT is considered. This set of objects contains the Vela pulsar and 2 bright flaring AGNs. Utilising *Fermi* data, the spectra of these bright objects with the highest statistics in the GeV range are used to constrain the photon spectral shape in the cut-off region as a tool for probing the acceleration, escape, and radiative loss processes giving rise to the particle energy distribution in this region. The list of these objects is provided in Table 1 along with the time window for which we extracted the spectrum. In the following subsections we report the results of this analysis. In Section 3, the potential improvements brought about by next generation instruments are considered. The benefits from the increase of the collection area on the data quality are demonstrated to be considerable. In Section 4, our conclusions on the present and future ability to accurately determine the underlying particle cut-off shape using gamma-ray instruments are made.

2. Analysis of the *Fermi*-LAT data

The analysis of the *Fermi*-LAT data for the AGNs was performed using the Science Tools v10r0p5[3] and the Instrument Response Functions (IRFs) "P8R2_SOURCE_V6" provided by the *Fermi* collaboration.[4]

The gamma-ray emission from the 2 blazars was investigated between 70 MeV and 300 GeV (100 MeV to 300 GeV for the Vela pulsar) energies using the `gtlike` routine to maximise the binned likelihood function [28]. The data were extracted from a square region 30° × 30° centred on the position given by the 3FGL catalogue using events with evtclass = 128 and evtype = 3.[5]

The source parameters were obtained fitting a model for each Region of Interest (RoI). These models contain the contribution of all the sources within 30° from the centre and thus includes sources outside the RoI. However all the sources more distant than 5° where fixed to the catalogue value. To take into account the diffuse emission we used the *Fermi* templates `iso_P8R2_SOURCE_V6_v06` and `gll_iem_v06` for the isotropic and galactic diffuse emission[6] respectively.

To determine the contribution of the background sources we have fitted the RoIs in 2 steps removing all of the sources with test statistic value less than 4 ($\sim 2\sigma$) for the null hypothesis of not having the source in that location. For these flaring sources this procedure was done on longer time intervals to avoid the influence of statistical fluctuations due to very short time-scales. To correctly estimate the flux at energies below 100 MeV and reduce the level of systematic uncertainties on the effective area, the analysis made use of the energy dispersion correction.

After this procedure to fix the background sources, we performed a final fit on the pulsar and the flaring state of the AGNs saving the parameters of the stretched exponential cut-off model and the value of the covariance between them. The spectral points were instead obtained by fitting the central source with a simple power-law and storing the normalisation value in each energy bin. The points of the Spectral Energy Distribution (SED) were then computed for bins with a test statistic (TS) value of at least 9 ($\sim 3\sigma$). The error bars computed with the Science Tools provided by

[2] 3FGL time interval
[3] http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
[4] http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
[5] These parameters for the event selection are the suggested ones for most of the Fermi-LAT analysis. This combination selects photon of SOURCE class that left a signal in both the front and the back part of the tracker. More information at http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data/LAT_DP.html
[6] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html