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Example of use of AMS Fast Simulator: spectral cutoff energy determination for Crab pulsar

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Abstract

AMS-02 is a large acceptance magnetic spectrometer which will be installed on International Space Station. Its main purpose is to measure charged cosmic rays. It will also be able to provide precise measurements in the gamma ray domain in an unexplored energy range from 1 GeV to more than 100 GeV. This range encloses the expected value of cutoff energy in the spectrum of pulsars. The AMS-02 sensitivity in the determination of this energy cutoff is investigated with use of AMS Fast Simulator.

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Contents

1 Introduction

The AMS-02 detector [1] will be able to detect cosmic ray gamma photons in two modes called conversion and single photon mode [2]. The number of photons detected by AMS-02 from an astrophysical source or a diffuse background are estimated using a software package called AMS Fast Simulator (AMSFS) [4]. In this package the detector performances are parametrized.

2 Crab pulsar

Crab pulsar (PSR B0531+21) is a remnant of a famous supernovae explosion from year 1054 which has been observed by Chinese astronomers. The nebula, which is a supernova remnant, has been observed for centuries, but the pulsar in the center of it has been discovered only in 1968 [3]. This first observations were in radio waves.

The pulsar is roughly 25 km in diameter and rotates once every 33 milliseconds. The outflowing relativistic wind from the neutron star generates synchrotron emission, which produces the bulk of the emission from the nebula, seen from radio waves through to gamma rays. The emission from nebula is continuous while the emission from pulsar is periodic.

The pulsar has been observed by SAS-2 and COS-B satellites in X and gamma rays. The most precise measurements in energy range from 0.1 GeV to 5 GeV up to date are provided by EGRET [5].

The pulsed emission has never been observed by Cerenkov telescopes, therefore probably the pulsar does not emit radiation at energy higher than 100 GeV. This agrees with models of pulsar radiation [6, 7], which forsee a cutoff (exponential or super-exponential) in spectrum of emitted photons.

The pulsar spectrum, in the GeV energy range, is expected to have a form of a power law with a cutoff E_{cut} . One of the proposed forms of the cutoff is the exponential one:

$$F(E) = I_0 \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{cut}}\right)^{\alpha} \tag{1}$$

where E_{cut} is expected to be in the range from 1 to 100 GeV, depending on the pulsar size, rotation period and a strength of pulsar magnetic field. This study is simplified to the case where $\alpha = 1$.

EGRET has not measured any cutoff. The results of its measurements, assuming simple power law flux (without exponential cutoff part), are:

$$I_0 = (4.11 \pm 0.16) \cdot 10^{-6}\ [\mathrm{cm}^2 \cdot \mathrm{s} \cdot \mathrm{GeV}]^{-1}$$
$$\Gamma = 2.15 \pm 0.04$$

with $E_0 = 0.274$ GeV.

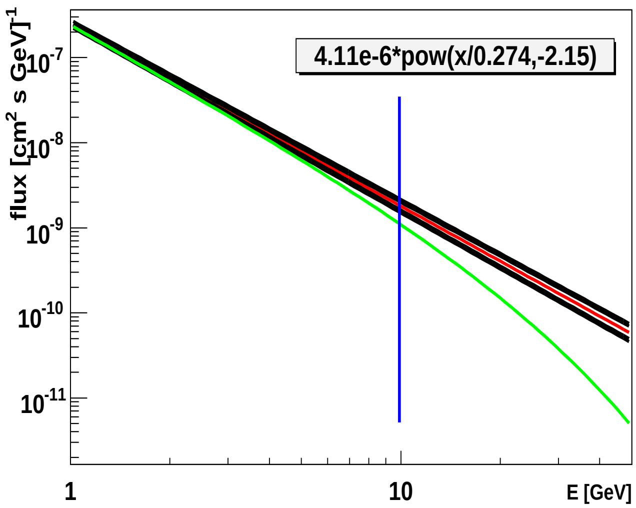

Figure 1: *Red and black lines present EGRET-measured Crab spectrum (measurement up to 10 GeV - vertical bar) with its errors. Green line is an example of the spectrum with 20 GeV exponential cutoff.*

This flux is plotted in Figure 1. The red line is the nominal value of flux, the black lines design the errors of EGRET measurements and the green line is an example of a flux in form of Formula 1, with cutoff energy equal to 20 GeV. The vertical, blue bar represents approximately the upper limit of EGRET measurements.

In this analysis, to simplify the procedure, we assume as fixed the parameters I_0 and Γ found by EGRET.

3 Estimation of the spectrum cutoff position

Measurement of any spectrum is performed in energy bins. The size of the bin depends on the available statistics of photons. In order to have statistically significant determination of a flux in a given energy bin, the bin should contain a certain number of photons. In this study we assume that there should be 10 photons in the less populated bin.

A typical astrophysical spectrum, as the one of Crab pulsar, decreases exponentially with the energy. Therefore the last bin contains the smallest number of photons. The size of the last bin and its position with respect to cutoff is a proposed estimator of the precision of the determination of the cutoff energy.

In this analysis we determine the energy value above which the 10 most energetic photons are detected (E_{10}). If this value is larger than cutoff energy E_{cut} than, assuming Equation 1, a trustworthy fit can be performed and cutoff energy can be determined. This estimator is simple and conservative.

In Table 1 the results of the calculation of E_{10} values for different values of E_{cut} are presented. It can be concluded that the cutoff value can be determined up to

E_{cut} (GeV)	E_{10} (GeV)	N_γ	$E_{cut} - E_{10}$ (GeV)
1	1.4	10.2	-0.4
2	2.55	10.0	-0.55
3	3.5	10.0	-0.5
5	5.1	10.0	-0.1
10	8	9.7	2
15	10	9.8	5
30	13.3	10.8	16.7
50	16.5	10.0	33.5

Table 1: *Results of AMSFS for spectra with different* E_{cut} *(see Equation 1). In the first column the value of* E_{cut} *is shown. In the second column the value* E_{10} *(energy above which AMS will detect only 10 photons), in the third column the amount of photons detected above* E_{10} *are presented. In the fourth one the difference between* E_{cut} *and* E_{10} *is shown.*

energy of 5 GeV. If the Crab spectrum has the cutoff at higher energies, its value will not be determined by AMS-02 measurements (unless a better estimator is found).

The dependence of the difference between E_{cut} and E_{10} as a function of E_{cut} value is presented in Figure 2. For the negative values the last bin is beyond the cutoff, so there is enough statistics to determine E_{cut} . The characteristic paraboloidal shape reflects the fact that the exponential cutoff diminishes also the flux for energies lower than E_{cut}. Therefore, for small values of E_{cut}, the whole measurable spectrum (measures start from 1 GeV) diminishes. Therefore the minimum of the parabola reflects the existence of the detection threshold of AMS-02.

4 Increasing the size of the experiment

The maximal value of Crab pulsar energy cutoff $E_{cut} = 5$ GeV is determined by the acceptance of the experiment and the duration of data taking period. A scenario in which AMS will stay on orbit longer than 3 years is possible because Space Shuttles will be decommissioned by the year 2011. Most of AMS detectors will be useless because of lack of magnetic field which will disappear when helium stock will evaporate. The only measurement which still will be possible are gamma ray measurements in electromagnetic calorimeter (ECAL). Therefore there is a motivation to make a simple estimation of AMS potential in case of longer data-taking period.

We define a boost factor which corresponds to increase of AMS sensitivity due to longer observational period or which might also correspond to different, larger detector (with larger acceptance). The measurable cutoff energy in function of a boost factor is presented in Figure 3. For example it can be read from this Figure that to measureme the cutoff energy of 20 GeV a boost factor of 65 will be needed.

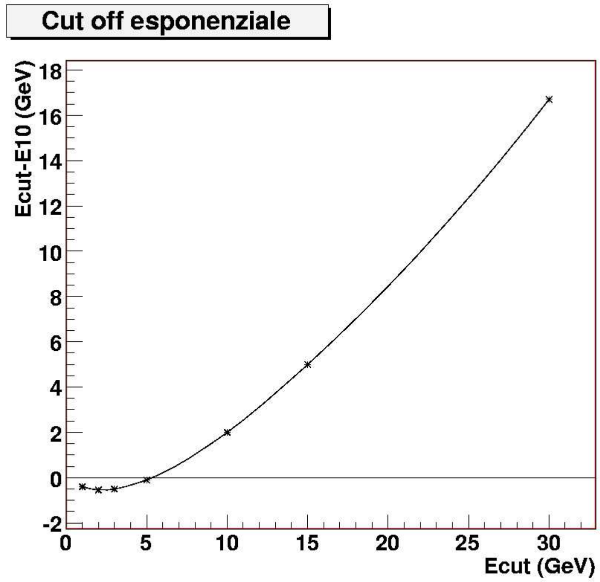

Figure 2: *Difference E_{cut}-E_{10} as a function of E_{cut} energy. The point in which the curve intersects with x-axis is the estimator of the highest detectable cutoff value.*

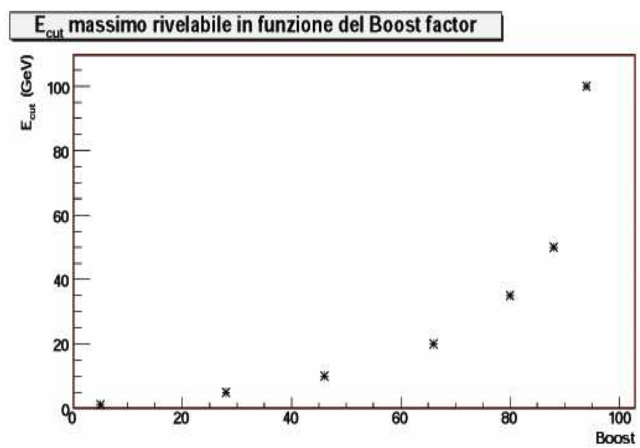

Figure 3: *EGRET flux (measurement up to 10 GeV) and an example of flux with 20 GeV exponential cutoff.*

5 Conclusions

Assuming the simple exponential cutoff we can conclude that AMS-02 will be able to detect the cutoff value for the Crab pulsar up to energy of 5 GeV. This value lies in the range of expected cutoff values.

This analysis is an exercise which can be improved in many aspects, for example:

- Assume the EGRET parameters (Equation 2) variable and refit the EGRET data points with the complete Formula 1.
- Test various values of the power of the exponential cutoff (α parameter in Equation 1).
- Consider the detector energy resolution which implies the smearing of the size of spectrum bins.
- Estimate the error of cutoff energy determination (as for example the size of the one before last bin).

Authors of these study want to draw attention of AMSFS team to the difficulty they had in automation of the search of E_{10} . They suggest that AMSFS team provides an example of a macro with a loop in which parameters of calculation (for instance the integration range or the spectral index of the source) change what would simplify studies based on parameter scan.

The study was presented as a dissertazione di laurea triennale in Fisica at the Universita degli studi di Roma "La Sapienza", by Daniele D'Armiento in October 2006

References

[1] C. Lechanoine-Leluc, "AMS - A magnetic spectrometer on the International Space Station", proceedings of the 29th International Cosmic Ray Conference (2005), Pune (India).

[2] M. Sapinski, "Detection and measurement of gamma rays with the AMS-02 detector", Proceedings of the 20th International Cosmic Ray Conference (2005), Pune (India)

[3] D.H. Staelin and E.C. Reifenstein, Science 162, 1481 (1968)

[4] J. Bolmont, M. Sapinski, I. Sevilla Noarbe, G. Lamanna "AMS-02 Fast Simulator User's Guide" AMS-note 2004-02-01

[5] P.L. Nolan et al., ApJ 450, 791 (1993)

[6] K.S. Cheng, C. Ho, M. Rudeman, ApJ 300, 500 (1986)

[7] J.K. Daugherty, A.K. Harding, ApJ 252, 337 (1982)