Preliminary indirect measurement of cosmic-ray proton spectrum using Earth's γ-ray data from *Fermi* Large Area Telescope

Patomporn Payoungkhamdee

Department of Physics, Faculty of Science, Mahidol University

E-mail: patomporn.pay@gmail.com

Abstract. Cosmic rays (CRs) are high-energy particles, mostly protons, propagating in space. The rigidity (momentum per charge) spectrum of CRs is well described by a power law for which the spectral index is approximately 2.8 around 30 - 1000 GV. Recent measurements by PAMELA and AMS-02 indicate an abrupt change of the CR proton spectral index at about 340 GV. When CRs interact with the Earth's upper atmosphere, γ rays can be produced and detected by space-based detectors. Here we use the Earth's γ-ray data collected by the *Fermi* Large Area Telescope along with a proton-air interaction model to indirectly determine the CR proton spectral index and compare against observations by other instruments.

1. Introduction

Cosmic-rays are high energy particles mainly come from outer space which can sometimes penetrate the geomagnetic field and interact with the Earth's atmosphere [1, 2, 3]. The interactions between CRs and the air molecules produce secondary particles, including γ rays, mostly in the forward direction with respect to the CR velocity. When observed from space, these CR-induced γ-ray emission of the Earth's atmosphere appears as a bright ring along the Earth's limb due to CRs grazing tangentially through the Earth's thin upper atmosphere and scattering photons towards the detector. The lower atmosphere and the physical Earth create the dark region in the center of the emission ring because they are opaque for γ rays (see Fig. 1 in [4]).

There are many possible acceleration mechanisms in the space that could produce high energy particles. The combined effects of the acceleration, propagation, and escaping from the Galaxy result in the power-law rigidity (momentum per charge) spectrum of CRs in the form $F \propto R^{\Gamma}$, where F is Flux, R is rigidity, and Γ is the spectral index. Note that for relativistic energy, the rigidity value in the unit of GV is very close to being directly proportional to the kinetic energy in GeV. The CR spectral index is approximately 2.7 for a very wide rigidity range, though there are a few known changes in the index value. One is an abrupt softening at 10^{15-16} GeV, known as the "knee," [5, 6] and the other one is a hardening at 10^{18-19} GeV, known as the "ankle" [7]. CRs produced by different sources or acceleration mechanisms may be characterized by having different spectral indices. Therefore, a spectral breaking feature could indicate a transition from a certain dominant source population of CRs to another. For example, CRs with energy above the ankle are presumably extragalatic. Finding spectral features will provide more clues to the origins of CRs.

In 2011, PAMELA detector indicated that there is a breakpoint of cosmic-ray protons spectrum around 240 GV [8]. Furthermore, AMS-02 also found a drastic change of cosmic-ray proton spectrum at around 336 GV [9]. From the previous work, 5 years of *Fermi* Large Area Telescope (*Fermi*-LAT) observation data has been analyzed to trace back the characteristic of CR proton spectrum where the result imply that there is a breaking of spectral indice around 200 GeV where the statistical significance is around 2σ [10]. In this work, 9 years of *Fermi*-LAT data would be use for finding the spectral indices of CR proton between energy hundred MeV to a TeV range.

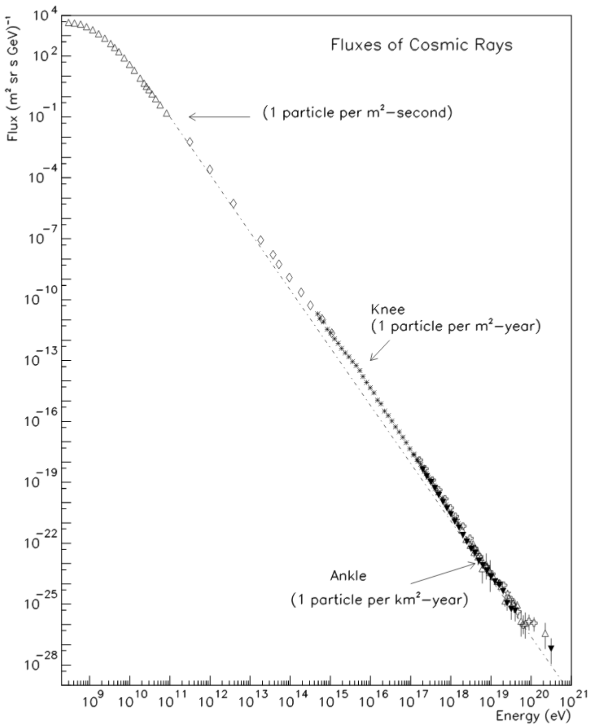

Figure 1. The all particle spectrum of cosmic rays, image taken from [4]

2. Methodology

2.1. Data selection and γ-ray flux extraction

Photon data with the latest reconstruction version (P8R2 ULTRACLEANVETO V6) of the telescope where the observation duration takes around 9 years (starts from 7 August 2008 to 16 October 2017). The energy range of photon is selected from 10 GeV to 1 TeV. The upper zone of earth's limb region could be determine by nadir angle from 68.4 to 70.0 where the coordinate figure has demonstrated in figure 2.

The observed flux is defined as differential flux where the governing equation for the calculation is represented as equation (1)

$$\textbf{Flux} \equiv \frac{dN_\gamma}{dE} = \frac{\int_{\text{Limb region}}(\text{Count map/Exposure map})}{\Delta\Omega\Delta E} \tag{1}$$

Where count map is filled up with selected γ-ray and exposure map represent the exposure time as well as effective area of spacecraft where the angle of incident CR has taken into account. Procedure of computation is begin with the requirement of 25 bins of histogram of the γ-ray flux which contain a various median of energy in each bin. Consequently, the number of count map and exposure map will be exactly the same as the energy bins. The calculation of exposure map is done by using log file of the spacecraft combine with

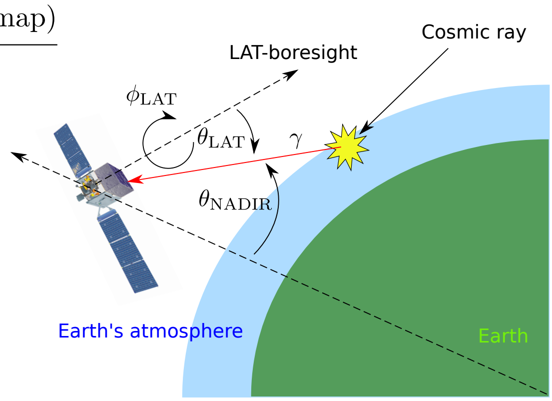

Figure 2. Schematic of γ-ray production

the responsiveness of the spacecraft which has to be consider in every step time while spacecraft is online. In addition, every step time of spacecraft require the coordinate transformation which cause a huge amount of computing process. That is the reason why paralleling processing with Master-Slave technique is applied in this work.

2.2. Interaction model

Incident CRs is modeled by a single power law (SPL) which contain one spectral indice and broken power law (BPL) where there is two spectral indices with a given breaking energy.

The model for a scattering amplitude from hadronic collision [11] that could produce a photon as a secondary product which could be detected by *Fermi*-LAT as equation 2.

$$\frac{dN_\gamma}{dE_\gamma} \propto \int_{E_\gamma}^{E_{\max}} dE' \frac{dN_p}{dE'} \frac{d\sigma^{pp\to\gamma}(E', E_\gamma)}{dE_\gamma} \tag{2}$$

For the real use case, the interaction of an alphaparticle with the air has a significant contribution to the secondary photon. A modification of He-air interaction could be applied by using a fraction of cross-section from a given atomic number [12]. The helium spectrum in rigidity is taken from the real measurement [13]. Then the input of the modified model is left only a proton spectrum.

$$\frac{dN_\gamma}{dE_\gamma}(E_\gamma) \propto \sum_{E_{\mathrm{inc,i}}} \left[\frac{E_{\mathrm{inc,i}}}{E_\gamma}\Delta(E_{\mathrm{inc,i}})\right] \left[f_{pp}\frac{dN_{\mathrm{H}}}{dE_{\mathrm{inc}}}(E_{\mathrm{inc,i}}) \left\{1 + \frac{\sigma_{\mathrm{HeN}}}{\sigma pN}\left(\frac{dN_{\mathrm{H}}}{dR}\right)^{-1}\frac{dN_{\mathrm{He}}}{dR}\frac{dR_{\mathrm{He}}}{dR_{\mathrm{H}}}\right\}\right] \tag{3}$$

2.3. Optimization

Optimizing a problem with multiple parameters might cause a local minimum which will cause an early stopping of the optimization proces before reaching to the global minimum. In this work, a simple gradient optimization with a set of different initial values yield a various output which implicitly imply that there are local minimum exists in this problem. To get rid of the local minimum, particle swarm optimization (PSO) is applied to find the best fit parameters [14].

3. Preliminary Results

The optimized parameters has shown in table 1. According to figure 3, secondary γ-ray product from both SPL and BPL model yield a similar product via hadronic collision in the atmosphere. In order to validate the indirect measurement of CR proton, comparing with a real observations is mandatory which has shown in figure 4. The normalization of this work is fitted PAMELA data to roughly scale the incident proton spectrum.

Table 1. Best fitted parameters

Proton CR model	Index 1	Index 2	E_{break} (GeV)
SPL	2.70	-	-
BPL	2.86	2.63	333

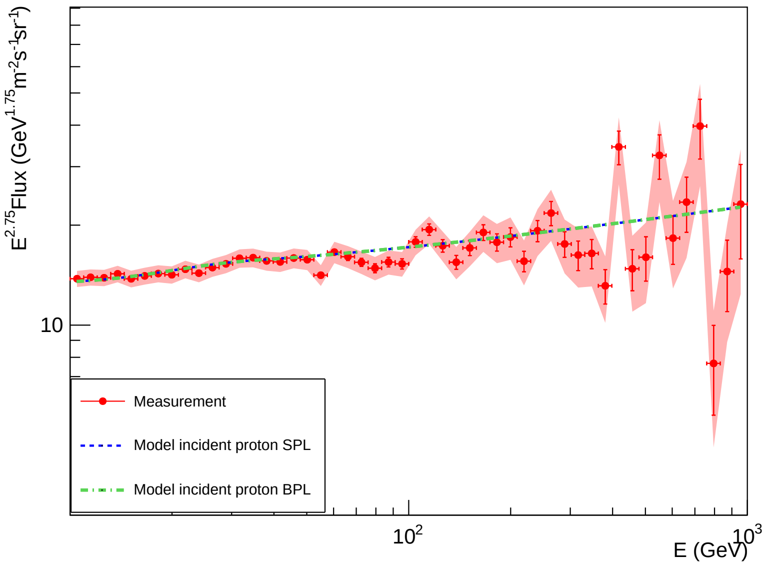

Figure 3. Measured γ-ray flux and the product from incident CRs

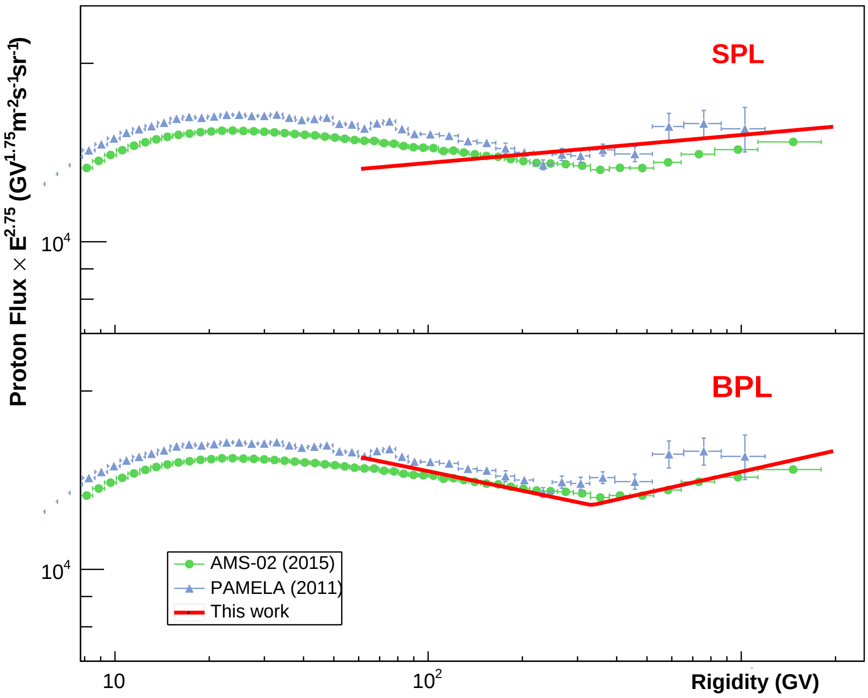

Figure 4. Best fitted proton CRs versus real observations

4. Discussion and future work

From the figure 3, a trend of incident proton model demonstrated that BPL has more consistency than SPL. Nevertheless, to determine the significance between two models require likelihood ratio test to evaluate the statistical level of confidence. In addition, statistical and total error including the instrument will be determined by performing Monte Carlo Simulation.

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