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Pulsar Simulation Tools for GLAST

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Abstract One of the most exciting targets of the Gamma-ray Large Area Space Telescope (GLAST) will be pulsars, that are still today among the most misterious sources in the sky. The GLAST LAT Collaboration has developed a detailed simulation of full LAT instrument. In order to better study the LAT science capabilities simulations of the most important classes of gamma-ray sources have been developed. Here are presented the current status of pulsar simulations for the GLAST LAT. *PulsarSpectrum* is a simulator developed for reproducing with high detail gamma-ray emission from pulsars. *PulsarSpectrum* takes into account advanced timing effects, e.g. period changes with time, barycentering effects and glitches. Other ancillary tools have been built to provide the simulator with a realistic population of pulsars and their ephemerides. All these tools are currently used by the GLAST collaboration for testing the LAT Science Analysis Environment and for studying LAT capabilities for pulsar science. They have been used for the generation of a simulated pulsar population in the Data Challenge 2 (DC2), one of the most important milestones in the development of the GLAST software. A description of *PulsarSimTools*, a suite of ancillary simulation tools is also given.

Keywords Pulsars · GLAST · Gamma-rays · Simulations

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1 Introduction

Pulsars are among the brightest non transient sources in the gamma-ray sky and can be used as unique probes for investigating the emission processes in extreme physical environments. Our knowledge of gamma-ray pulsar physics increased thanks to the Compton Gamma Ray Observatory (CGRO) that operated in the period 1991-2000. During CGRO era four new pulsars were discovered, increasing the number of presently known gamma-ray pulsars to seven [6]. Another breakthru regarding gamma-ray pulsars is foreseen with the launch of the Gamma-ray Large Area Space Telescope (GLAST), planned for autumn 2007. GLAST is an international space mission entirely devoted to the study of the gamma-ray Universe. GLAST will carry a main instrument, the Large Area Telescope (LAT), a pair conversion telescope designed for detection of photons from about 30 MeV up to 300 GeV, and the GLAST Burst Monitor (GBM), specifically designed for GRB observations. Based on sophisticated detectors from the High Energy Physics, GLAST will have a much high resolution and sensitivity than its predecessor EGRET aboard CGRO. The

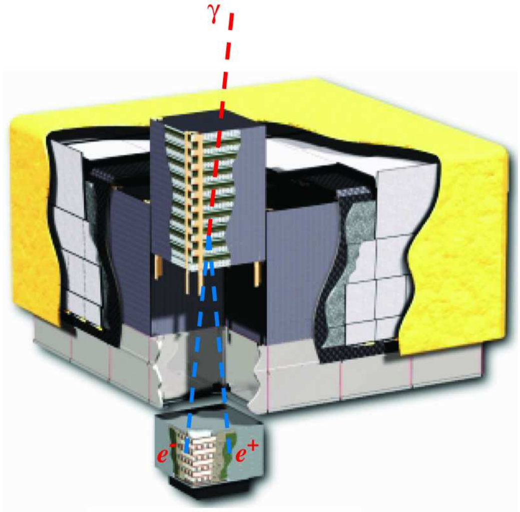

Fig. 1 The Large Area Telescope (LAT), the main GLAST instrument. An incident gamma-ray enters the detector and produce a $e^{-}e^{+}$ pair, whose tracks and energy are reconstructed in order to derive the direction and energy of the incoming photon.

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GLAST Large Area Telescope (LAT) (Fig. 1), is a pair conversion telescope based on advanced high energy detectors. It consists of a precision silicon tracker, an hodoscopic calorimeter for reconstructing direction and energy of gamma-rays, and a segmented anticoincidence shield for particle background rejection. The LAT high sensitivity (∼2×10^{-9} ph cm$^{-2}s^{-1}$ in 1 year) and large peak effective area (>8000 cm^2) will permit the discovery of many new pulsars: the estimates range between tens to hundreds depending upon the theoretical scenario considered [7]. Moreover the low dead time of the instrument (∼20 μs) will allow the detailed reconstruction of pulsar lightcurves. One of the most exciting possibilities of the LAT will be the coverage of the energy window from 30 GeV up to 300 GeV, a spectral window where the sky is still quite unexplored. At these energies the theoretical models make different predictions on the high energy spectrum, then the LAT spectral coverage will be of primary importance for constraining and discriminating among the models. Presently the thoretical models for pulsar gamma-ray emission are divided in two main classes. According to the Polar Cap models the emission takes place above the magnetic poles of the pulsar and the high-energy emission show a sharp cutoff due to gamma-ray absorption in high magnetic fields [3]. In the Outer Gap models [1] the emission comes from the outer vacuum gaps near the light cylinder and the high-energy spectrum has a softer cutoff, that can be modeled with a simple exponential function [4].
In order to better understand the capabilities of GLAST for pulsar science we developed *PulsarSpectrum*, a program that simulates gamma ray emission from pulsars with high detail. The simulator can be easily interfaced with the full MonteCarlo simulation of the LAT, such that the generated gamma-ray photons from the source are folded through the Instrument Response Function of the LAT. Also the *PulsarSimTools* suite is presented, which consists of a set of ancillary tools useful for generating realistic pulsar parameters.

2 The *PulsarSpectrum* Simulator

2.1 General Overview

The basic idea of *PulsarSpectrum* is to build a bidimensional histogram representing the differential flux vs. energy and pulsar phase. This histogram contains all the informations about lightcurve and spectrum. How it is built depends upon the chosen model, e.g. a phenomenological model, based only on observations. Currently two models have been included. The first implemented model was phenomenological, since it is more flexible. An additional model recently implemented allow the user to simulate pulsars with an arbitrary photon distribution in phase and in energy. The input parameters of the simulator can be divided in two categories:

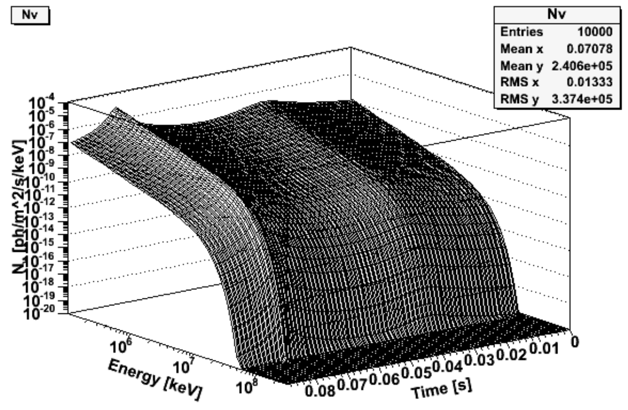

Fig. 2 An example of a 2D histogram generated by *PulsarSpectrum* for simulating a pulsar with a spectrum similar to Vela pulsar

- *Observational parameters*, which characterize the general parameters of the simulated pulsar;
- *Model-dependent parameters*, that define which model will be used for simulation and the set of parameters used by this model. There are 5 free model-dependent parameters;

All parameters are placed in two specific data files used by *PulsarSpectrum*. *PulsarSpectrum* creates the lightcurve and the spectrum and combines them to obtain a two-dimensional matrix that represents the flux in ph m^{-2}s^{-1}keV^{-1}. An example of such an histogram for a simulated pulsar similar to Vela is in Fig. 2. The photons are then generated such that the interval between two subsequent photons is determined by the flux integrated over the energy range of interest. The generated photons can then be sent to the MonteCarlo simulation of the LAT, in order to obtain the distribution of the photons reconstructed by the LAT.

2.2 *PSRPhenom*, the Phenomenological Model

The phenomenological model (*PSRPhenom*) allows the user to generate pulsar lightcurves in a general way using a single or double Lorenzian peak profile whose shape is determined from random generated numbers. The lightcurve can be generated alternatively from a user-provided profile, e.g. for simulating the EGRET pulsars. The spectral shape is specified by an analytical form, a power law with exponential cutoff as in [2]:

$$\frac{dN}{dE} = K(\frac{E}{E_n})^a exp(\frac{E}{E_0})^{-b} \quad (1)$$

The normalisation constant K is determined by the photon flux in the range 100 MeV- 30 GeV, in order to have flux compatible with the fluxes in the 3^{rd} EGRET Catalog [5]. The other spectral parameters can be varied; the values for the EGRET pulsars can be obtained as in [2].

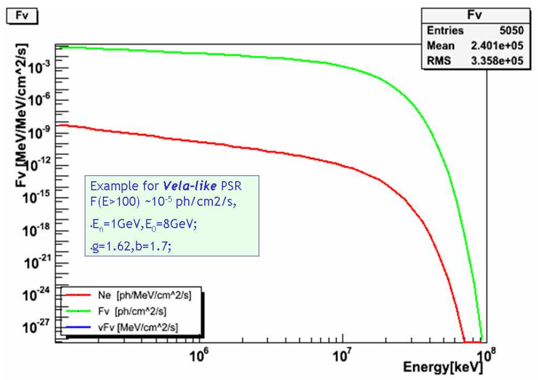

Fig. 3 The input spectrum for a Vela-like pulsar using phenomenological model. The spectral parameters have been obtained from [2].

As an example, in Fig. 2 is presented an histogram for a *Vela-like* pulsars, i.e. a simulated pulsar with spectrum and lightcurve similar to the Vela pulsar.

2.3 The *PSRShape* Model

An additional model has been also implemented, that does use an user-defined histogram. In this way it is possible to implement directly the predicted spectrum from a specific theoretical model, and also to simulate a phase-dependent spectrum, in order to study the LAT capabilities for phase-resolved spectroscopy. In the Fig. 4 the input models for a phase-averaged Polac Cap spectrum [3] and a phase-averaged Outer Gap spectrum [4] is shown. Once a model is defined, the user can change the normalization, preserving only the shape of the phase-energy model, entering the total flux above 100 MeV. Otherwise a normalization will be not included and the flux is taken directly from the input histogram.

2.4 Timing Issues

Once the differential flux histogram is created the time interval between two subsequent photons is computed according to the flux. The strategy adopted is to compute the mean photon rate and then to calculate the interval to the next photon according to Poisson statistics. The interval between two photons is computed assuming that the pulsar period does not change with time and the photons arrival times are computed into a reference system fixed relative to stars, but this is not the "real world". Pulsar timing is affected by more complicate effects, as (1)- The motion of GLAST through the Solar System and the relativistic effects due to gravitational well of the Sun (see 2.5); (2)- Period changes with time (see 2.6). For pulsars in binary systems an additional modulation to the orbital period should be taken into account. For a precise pulsar simulator intent to produce a realistic list of photon arrival times we need to include all these effects (to transform to the observational frame). All these procedures are now implemented in the code and only the binary demodulation is not yet implemented. A secondary correction Δt_{tim} is summed to the interval between photons in order to consider all these timing effects.

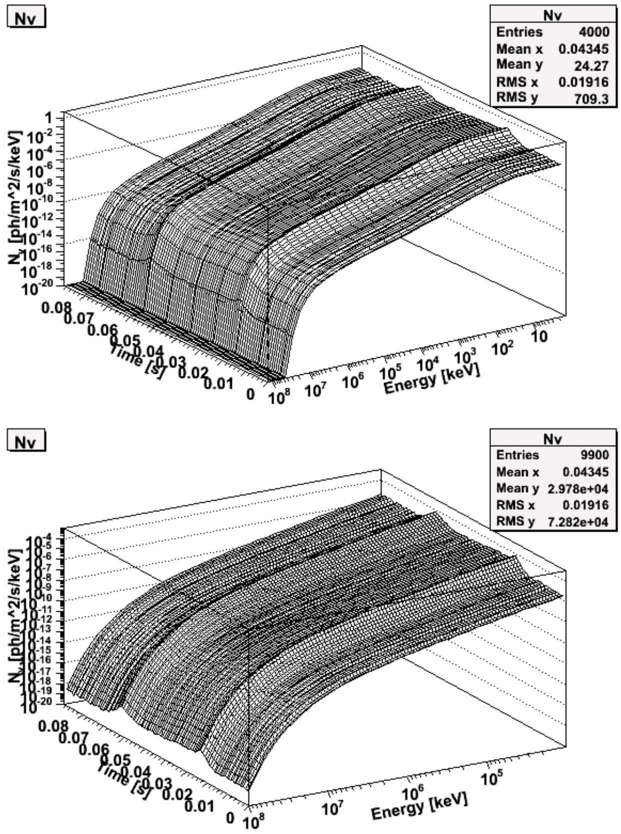

Fig. 4 Two example of pulsar models given in input to the PSRShape model. Above: A Polar Cap phase averaged spectrum from [3]. Below: An Outer Gap phase averaged spectrum from [4]. The sharper cutoff for the Polar Cap is clearly visible

2.5 Barycentric Effects

The first step to analyze pulsar data is the conversion from the arrival times at the spacecraft, usually expressed in Terrestrial Time TT or TAI, to the arrival times at the Solar System barycenter, expressed in Barycentric Dynamical Time TDB. Taking into account both the motion of spacecraft through space and the general relativistic effects due to the gravitational field of the Sun (i.e. Shapiro delay), the simulator computes the opposite of the barycentric correction by considering the position of the Earth and of the spacecraft in the Solar System, and the position of the Sun. The accuracy for the computation of these corrections is hard-coded in the program.

2.6 Period Change and Ephemerides

The rotational energy of a radio pulsar decreases with time and hence the period increases with time. For gamma-ray pulsar radio ephemerides are fundamental for assigning the correct phase to each photon. If we know the frequency $f(t_0)$ and its derivatives $\dot{f}(t_0)$ and $\ddot{f}(t_0)$ at a certain time t_0, known as *epoch*, the phase is then:

$$\phi(t) = int[f(t_0)(t-t_0)+\frac{1}{2}\dot{f}(t_0)(t-t_0)^2+\frac{1}{6}\ddot{f}(t_0)(t-t_0)^3]. \quad (2)$$

where int indicate the integer part. The interval between two photons must be also corrected for this effect. In the parameters file the user can specify a set of ephemerides with the relative epoch of validity expressed in Modified Julian Date. The simulator then computes the opportune arrival time such that, after applying the barycentric corrections and then the Eq. 2, the correct phase is obtained.

3 The *PulsarSimTools* Suite

In order to support the pulsar simulations and provide realistic parameters to *PulsarSpectrum* we developed a suite of ancillary C++ tools, that we called *PulsarSimTools*. The aim of these tools is to act as infrastructure for producing realistic set of simulated pulsars and to format the paramaters to be input to *PulsarSpectrum*.
The main components of *PulsarSimTools* are:

– **Population Synthetizer**: Generates a pulsar population in a phenomenological way. Positions and periods of pulsars are extracted random according to the pulsars in the ATNF Radio Pulsar Catalog. Spectral parameters and fluxes are derived assuming a specific theoretical model;
– **Ephemerides generator**: Creates ephemerides for every simulated pulsar;
– **TH2DMaker**: Provide a suitable 2D model to be given in input to the PSRShape model in *PulsarSpectrum*;
– **PulsarSetsViewer**: Plotting utility;
– **PulsarFormatter**: From synthetized pulsar population data creates suitable input data files to *PulsarSpectrum*;

4 Conclusions

Pulsar simulations are very useful to study the response of the GLAST Large Area Telescope with some detail. To this scope we developed *PulsarSpectrum* simulator and a suite of ancillary tools that allow the user to generate a suitable set of parameters for a realistic pulsar population.It is possible to choose a phenomenological model, which is based on a analytical form for the spectrum, or a more flexible model, through which the user can insert a specific phase-energy distribution of photons. All the simulation tools here presented have been used during the LAT Data Challenge 2 (DC2), a milestone in the development of the LAT analysis and simulation software. During the DC2, scientists analyzed a set of 55 days of simulated data in order to validate LAT MonteCarlo, study instrument response functions, exercise analysis tools and study LAT capabilities. For the DC2 an high-detailed model of the gamma-ray sky was created, including the presently known classes of gamma-ray sources and possibly new ones. A population of about 400 pulsars have been generated for DC2 using *PulsarSpectrum.*
Some extensions to this simulator work needs to be included, mainly the possibility to simulate pulsars in binary systems. In this way also the LAT capabilities of studying pulsars in binary systems could be explored, then this issue is one of the next steps in developing the pulsar simulation tools.

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