Gamma-ray Pulsar Simulations for the Gamma-ray Large Area Space Telescope (GLAST)

M. Razzano$^{1,2}$

$^1$Istituto Nazionale di Fisica Nucleare, Pisa sect., Largo B.Pontecorvo 3, 56100 Pisa, Italy. email:massimiliano.razzano@pi.infn.it

$^2$on behalf of the GLAST LAT Collaboration

Abstract. We present here the current status of pulsar simulations for the Large Area Telescope, the main instrument on the GLAST mission. We present PulsarSpectrum, a pulsar simulator that can reproduce 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 in the GLAST collaboration for testing the LAT Science Analysis Tools and for studying LAT capabilities for pulsar science. They have been used also for generating a simulated pulsar population for the Data Challenge 2 (DC2), one of the most important milestones in the development of the GLAST software. During the DC2, scientists analyzed a set of 55 days of simulated data in order to validate LAT Monte-Carlo, study instrument response functions, exercise analysis tools and study LAT capabilities. This contribution also contains results of some analysis performed during DC2 on EGRET pulsars.

1. Introduction

Pulsars are among the most exciting gamma-ray sources in the Universe and can serve as unique sites for the study of emission processes in extreme physical environments. The Gamma ray Large Area Space Telescope (GLAST) will increase dramatically our knowledge of gamma ray pulsars physics. In particular, the Large Area Telescope (LAT), the main GLAST instrument, will provide more detailed observations of the known gamma-ray pulsars and potentially will discover many new pulsars that emit gamma rays. To better understand the capabilities of GLAST for pulsar science we developed PulsarSpectrum, a program that simulates gamma ray emission from pulsars and a set of ancillary tools that can create simulated pulsar data to be used with PulsarSpectrum. This simulator can be easily interfaced with the MonteCarlo software that simulates the response of the LAT.

Today seven high-confidence and three low-confidence gamma-ray pulsars are known and this numbers will increase with the observations of GLAST, scheduled for launch in the fall of 2007.

The GLAST Large Area Telescope (LAT) (Fig. 1), is a pair conversion telescope based on the most advanced high energy detectors. It consists in a precision silicon strip tracker, an hodoscopic calorimeter and a segmented anticoincidence shield for particle background rejection. The LAT high sensitivity ($2 \times 10^{-9}$ ph/cm$^2$/s) and effective area ($>8000$ cm$^2$) will permit the discovery of a lot of new pulsars: the estimates range between tens to hundreds depending upon the theoretical scenario adopted. Moreover the low dead time of the detector (20 $\mu$s) 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 still unexplored range. At these energies the theoreti-
Table 1. The PulsarSpectrum parameters.

| Type of Parameter               | Parameter                      |
|---------------------------------|-------------------------------|
| Observational                   | $RA, Dec, \text{flux, } t_0, f(t_0), f'(t_0), f''(t_0)$ |
| Model-dependent                 | $\text{Model, } E_{\text{min}}, E_{\text{max}}, \text{Random seed,}$ $5 \text{ free parameters}$ |

$t_0$ indicates the epoch of the ephemerides

cal models make different previsions on the high energy spectral cutoff and the spectral coverage of LAT will be of primary importance for constraining and discriminating among the models. In order to study the LAT response to specific gamma ray sources, various simulation packages have been developed.

2. The PulsarSpectrum simulator

2.1. General overview

The basic idea of PulsarSpectrum is to construct a bidimensional histogram representing the differential flux vs. energy and pulsar phase. This histogram contains all the basic informations about lightcurve and spectrum. How it is built depends upon the model we want to use: for example a phenomenological model, based only on observations, or a physical one, based on a specific theoretical model. Currently two models have been included. The first model implemented was phenomenological, since it is more flexible and completely independent from the theoretical emission scenario. A second model recently implemented allow the user to simulate pulsars with an arbitrary photon distribution in phase and in energy. This model can in fact use a 2D histogram that can be provided by other external programs.

The input parameters of the simulator can be divided in two categories and are listed in the Table 1:

- **Observational parameters**, which characterize the general parameters of the 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 parameters that leave to the user the freedom to adjust the model.

All parameters are placed in two specific data files used by both PulsarSpectrum and the LAT simulation tools. PulsarSpectrum creates the lightcurve and the spectrum from these parameters and combines them to obtain a two-dimensional matrix that represents the flux in $\text{ph/m}^2/\text{s/keV}$. An example of such an histogram for a simulated pulsar similar to Vela is in Fig. 2. The photons are then extracted such that the interval between two subsequent photons is determined by the flux integrated over the energy range of interest.

2.2. The phenomenological model

The phenomenological model 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. This is useful for simulating the already observed gamma ray pulsars. The spectral shape is assumed to be a power law with exponential cutoff (according to [1]), as in the observed gamma-ray pulsars and can then be modeled as:

$$\frac{dN}{dE} = K \left( \frac{E}{E_\alpha} \right)^a \exp \left( \frac{E}{E_0} \right)^{-b}$$  \hspace{1cm} (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 3rd EGRET Catalog. The other spectral parameters can be varied; the values for the EGRET pulsars are obtained from real data by fitting procedures (See e.g. [1]). As an example, in Fig. 2 is presented an histogram for a Vela-like pulsars, i.e. a simulated pulsar with characteristics similar to the Vela pulsar. The lightcurve has been derived from EGRET observations while the spectral parameters from a multi-wavelength fit as reported in [1] are displayed in Fig. 3.

2.3. 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

Fig. 2. An example of a 2D histogram generated by PulsarSpectrum for simulating a pulsar with a spectrum similar to Vela pulsar
the mean photon rate and then to calculate the interval to the next photon according to Poisson statistics. Then a secondary correction $\Delta t$ is summed to this interval in order that the photon distribution follow the input lightcurve. 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. This is not the "real world". Pulsar timing is affected by more complex effects, as (1)- The motion of GLAST through the Solar System and the relativistic effects due to gravitational well of the Sun (see 2.3.1); (2)- Period changes with time (see 2.3.2). 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. The real arrival time of a photon from a pulsar must be first barycentered and then phase assigned.

2.3.1. 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.

2.3.2. 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 science the 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:

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

(2)

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. Gamma-ray pulsars in the LAT Data Challenge 2

*PulsarSpectrum* have been used by the GLAST LAT Collaboration for simulating pulsars in the LAT Data Challenge 2. The Data Challenge 2 (DC2) was an important milestone for the preparation of the analysis and simulation software for the GLAST mission. For the DC2 a simulated 55-days long LAT observation of the whole sky have been generated, and the simulated data have been provided to the scientists of the Collaboration. The main goals of the DC2 were to study and validate the LAT MonteCarlo, to exercize the Analysis Tools under development for GLAST and to better study the LAT Instrument Response Functions. Using DC2 simulated data, a group of LAT scientists have worked on these from the begin of March to the end of May (date of official DC2 Closeout
One of the most important efforts in the DC2 was the composition of an high-detailed simulation of the gamma-ray sky (see Fig. 1). This simulated sky was built by using a set of programs capable to simulate the different gamma-ray sources. Not only the current known gamma-ray sources discovered by EGRET have been included, but also a lot of new sources, in order to push down the sensitivity limit of the detected sources. Also possible new classes of gamma-ray sources have been included, such X-ray binaries and microquasars.

The pulsar component was entirely simulated by PulsarSpectrum and was composed by some subclasses of pulsars. There are the six gamma-ray pulsars detected at EGRET energies, displayed in Fig. 4, and some other real radio-pulsars that are within error box of some 3EG sources. The remaining pulsars were not actually real pulsars, but simulated pulsars that have characteristics similar to the current known pulsars. These were divided in two subgroups, a set of isolated pulsars and a set of millisecond pulsars. A database containing the timing solution for some pulsars has been provided to DC2 users. However for some gamma-ray pulsars the timing solution have not been provided, in order to leave to the DC2 people the possibility to study techniques for finding Geminga-like pulsars with no radio counterparts. In Fig. 5 and 6 are displayed the reconstructed phase curves of the simulated Vela and Geminga pulsar using DC2 simulated data.

These curves showed a profile very similar to the real EGRET profile, but this is not a suprise since the EGRET data have been used for shaping the input lightcurve for EGRET pulsars present in the DC2. With comparison of EGRET it is remarkable the better statistics achieved with the LAT in 55 days in comparison to the EGRET curves, as reported e.g. in [2].

4. Conclusions

Pulsar simulations are very important to study the GLAST LAT capabilities to probe these gamma-ray sources. We present here the latest results in pulsar simulations using the PulsarSpectrum simulator, able to reproduce timing and spectral features of gamma-ray pulsars with high detail. PulsarSpectrum has been successfully used by the GLAST collaboration for testing the functionality of the LAT Science Analysis Tools, a set of analysis programs specifically designed to analyse the LAT data after launch. An important event in the preparation of the GLAST mission was the Data Challenge 2, during what a 55-days LAT observation of the full sky have been generated. Pulsars included in DC2 sky have been simulated with this simulator, providing LAT scientists simulated data from a realistic gamma-ray pulsar population. The DC2 has been also a good chance to exercise the pulsar simulator and to show that PulsarSpectrum can be used by the GLAST Collaboration for better exploring the LAT detecting capability on pulsars.

References

Nel H.I. and De Jager O.C. 1995, Astrophysics and Space Science 230, 209
Kanbach G., 2002, Proocedings of the 270 Max-Plank Conference on Neutron Stars, Pulsars and SUpernova Remnants, 91
Thompson D.J., astro-ph/0312272