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October 6, 2020

Gamma-ray polarimetry of the Vela pulsar with the *Fermi*-LAT

1 Thesis overview

For 70 years [1, 2] the astrophysical community and particularly the γ-ray astronomy community have been dreaming of operating a γ-ray polarimeter in orbit, i.e., a telescope that can measure the fraction and the direction of the linear polarization of the radiation, something which would bring an additional and critical observable to the understanding the emission mechanisms of many types of sources. For the first time, from recent works carried out within the gamma-ray astronomy group at LLR and within the Geant4 group at LLR, and thanks to the quantity and the quality of the data acquired by Large Area Telescope (LAT) [5] on the spatial mission *Fermi* over the past twelve years, the possibility arises of performing the measurement in the energy range between the MeV and GeV, on one of the brightest sources in the γ-ray sky in this energy range: the Vela pulsar.

The objective of the thesis is **the first measurement** of the fraction and of the direction of the linear polarization of a cosmic source, the Vela pulsar, in the e^+e^--pair-conversion regime.

2 Thematic: gamma-ray astronomy

Photons are electrically neutral and therefore enable an **astronomy**, each photon being recorded independently and associated to a cosmic source. The study of their spectra, of the possible flux variations, eventually of the spatial extent of a source enables an **astrophysics**, an understanding of the processes at work inside the object. The gamma-ray range that can be observed presently extends from $\approx 100\,\text{keV}$ to $\approx 100\,\text{TeV}$ to, experimentally covered by

- $E < 30\,\text{MeV}$, Compton detectors ($\gamma e^- \rightarrow \gamma e^-$), on spatial missions;
- $30\,\text{MeV} < E < 3\,\text{TeV}$, pair-conversion ($\gamma Z \rightarrow e^- e^+ Z$), on spatial missions; (the ion Z recoils but is not detected).
- $E > 30\,\text{GeV}$, pair-conversion in air, followed by the development of an electromagnetic shower, the Cherenkov light of which is detected on the ground.

3 Domain: polarimetry

Cosmic sources can't emit gamma rays thermally. The gamma-ray sky is therefore dominated by non-thermal processes, often associated to a magnetic field (synchrotron radiation "RS", curvature radiation "RC"), a radiation that is linearly polarized, or due to particle interactions that conserve polarization ("inverse" Compton scattering, ($e^-\gamma \to e^-\gamma$), ICS). In contrast, the hadronic interactions of (charged) cosmic rays (CR) with interstellar matter at rest produce copious spin-zero π^0s and therefore non polarized photons, enabling to map the location of the CR acceleration centers.

Understanding the radiation processes in **pulsars** is limited that the large number of unknown variables (angle with axis and field, viewing angle, field magnitude ...) in regard to too few observables: we don't even know the location of the gamma-ray emission (*outergap, two-pole caustic, current sheet* ..). For an emission outside the light cône, ("*current sheet*"), for example, the transition between synchrotron radiation and curvature radiation, for the Crab pulsar, would be tagged by the polarization leap just below 100 MeV [3].

For **blazars**, active galactic nuclei (AGN) a jet of which is (almost) aligned towards the observer, a high gamma-ray polarization fraction would point to a lepto-hadronic jet content (ionized matter), while a small fraction would point to a leptonic jet (electrons-positrons) [4].

In the low-energy range that extends from radio waves to X-rays, polarimetry is a powerful diagnostic of the nature of the emission processes. For gamma-rays, unfortunately, this diagnostic has been sorely lacking up to now.

4 Context

In the Compton regime, a number of future missions are being considered, [6, 7], that are sensitive to polarization below $\approx 1\,\mathrm{MeV}$.

For conversion to pairs (the threshold is $2m_ec^2 \approx 1\,\mathrm{MeV}$), the measurement is based on the analysis of the so-called azimutal angle, φ, that references the orientation of the final state in a plane perpendicular to the direction of the incoming photon [1]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varphi} \propto \left(1 + A \times P\cos(2(\varphi - \varphi_0))\right). \tag{1}$$

- A is the polarization asymmetry of the conversion process;
- P is the polarization fraction of the incoming radiation;
- φ_0 is the polarization angle of the radiation from that source.

The polarized differential cross section has been known for a while [2], but a characterization of space-compatible experimental systems has been achieved only recently [8] by the gamma-ray group at LLR (the HARPO project), with a dedicated prototype detector [9].

In passing, we have demonstrated that the event generators of the Geant4 software that is used for the detailed simulation of particle detectors and gamma-ray telescopes, were showing major flaws for a study of pair-conversion telescopes [10]. And their polarized generator is wrong [10]. We have therefore implemented our generator of the full (5D) differential cross section [11] and made it available since Geant4 version 10.5 [12].

The gamma-ray telescopes that are in orbit presently [5, 13] and the projects that are being developed [7, 6], all use active targets (combined converter-tracker systems) based on a silicon-strip detector (SSD) mille-feuille, either with [5, 13] or without [7, 6] additional high-Z converter foils (such as tungsten). With that detector type, a non-zero value of the effective polarization asymmetry, A_{eff} (that is, taking into account the detector effects [14]) has **never** been demonstrated [15, 6]. This is why these studies have used an **assumed value** of A_{eff} to guesstimate a sensitivity [15, 6].

5 Method

The NASA *Fermi* mission has been in orbit since 2008, has acquired more that a billion high-quality gamma-ray photon candidates from an energy of $\approx 30\,\text{MeV}$ to above $1\,\text{TeV}$. For each of the brightest sources, the *Fermi*-LAT software is able to select high-purity samples of several millions photons.

With a dedicated event reconstruction method and tools developed locally, I am presently characterizing the potential of SSDs for polarimetry in the pair-creation regime. I observe a maximum sensitivity at $\approx$ 100-200 MeV with a fall to zero at $\approx$ 20 MeV on the low-energy side and at $\approx$ 5 GeV on the high-energy side. The effective polarization asymmetry is peaking at $\approx$ 4% [19], which is lower than that we achieved with our dedicated polarimeter (HARPO: 10% [8, 9]) and than the QED value (16-17% [18]), but which should enable a significant measurement of the brightest sources of the gamma-ray sky, pulsars in the first place.

6 The Ph. D

The thesis will take place in the *Fermi* group at LLR (4 CNRS scientists with research topics such as pulsars [16] and AGNs [17]), for a duration of three years (01 Oct. 2021 – 30 Sept. 2024).

The reference doctoral school is ED IPP (Ecole doctorale de l'Institut Polytechnique de Paris.

7 Profile and skills required

Master's degree in particle physics or astroparticle physics. Mastering the basics of the C++ / ROOT software will be welcome.
Efficient use of either French or English is required. Minimal use of English is needed.

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