Early *Fermi*-LAT observations of the Vela pulsar

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The Vela pulsar is one of the first targets of the Large Area Telescope, the main instrument aboard the *Fermi* Gamma-ray Space Telescope, successfully launched in June 2008. I will report on the main results coming out from the early observations of this pulsar during the first months following the launch of *Fermi*. During this period the LAT collected $\sim$ 32400 pulsed photons above 0.03 GeV and the light curve shows structures as sharp as 0.3 ms, as a result of the high timing resolution of the LAT combined with the high-quality radio ephemerides provided during the radio monitoring campaign. The study of the light curve at different energies shows that the pulse profile evolves with time, revealing a third peak at high energy. The study of the off pulse component has been useful for putting limits on the steady plerionic emission. Moreover, the analysis of the spectrum provides a much more improved measurement of the high-energy cutoff, one of the most powerful tools for constraining scenarios of gamma-ray emission in pulsars.

1 Introduction

The Vela pulsar is the brightest persistent point source in the gamma-ray sky. Because of its brightness, this source is the best studied gamma-ray pulsar, together with Crab and Geminga. Gamma-ray pulsars are believed to contribute substantially to the galactic population of EGRET unidentified sources [13], but so far only few of them have been firmly identified [6]. Gamma-ray pulsars are one of the most important targets for the recently launched *Fermi* Gamma-ray Space Telescope (previously known as GLAST). *Fermi* is an international space mission devoted to the study of the high-energy cosmic gamma-rays and carries two main instruments, the Large Area Telescope (LAT) [1] and the Gamma-ray Burst Monitor (GBM). The Large Area Telescope (LAT) is a pair-conversion telescope designed for the detection of gamma rays from $<$30 MeV to $>$ 300 GeV [1]. The Vela pulsar (PSR B0833-45, PSR J0835-4510) has been one of the primary targets for *Fermi* after its successful launch of 11 June 2008. Because of its brightness, Vela is a classical target for first observations of gamma-ray space telescopes and for calibration and tuning of the instruments. This pulsar was discovered as a radio source with period of P=89 ms in the Vela supernova remnant [9]. It is bright ($S_{1.4GHz} \sim 1.5$ Jy), is surrounded by an X-ray nebula and is immersed in a radio synchrotron nebula From spin parameters it is possible to estimate the basic characteristics of the pulsar, that turns out to be quite young, with a characteristic age $\tau_c = \frac{P}{2\dot{P}} \sim 11$ kyr, and energetic, with a spin-down luminosity $\dot{E}_{SD} = 6.9 \times 10^{36} I_{45}$ erg/s[a]. The Vela pulsar is located at a distance of D = 287 pc, as based on recent VLBI parallax measurements [3]. Vela was detected as a gamma-ray emitter during the SAS-2 mission [12] and shows two peaks separated by 0.42 in phase, and past missions showed evidence of a cutoff in the range 2-4 GeV. Moreover, the Vela pulsar is one of the best targets for measuring high-energy cutoff, the most sensitive tool to test pulsar gamma-ray emission models [4].

2 LAT observations of the Vela pulsar

The initial observations of the Vela pulsar were based on 35 days of on-orbit verification tests and the initial $\sim$ 40 days of the on-going first year sky survey. We report here the results based on this initial observations, and more details can be found at [2]. During the initial period of the *Launch and Early Orbits Operations*, the instrument configuration was being tuned for optimum performance and the results of these studies were used to verify the LAT photon selection, effective area, timing, photon energy measurement and the variation of the Point Spread Function (PSF) with energy. Since the Vela pulsar is young, it exhibits substantial timing irregularities, then it is necessary to have contemporary radio ephemeris. The radio ephemeris is obtained using observations made with the 64-m Parkes radio telescope as part of the overall program of pulsar timing in support of the *Fermi* mission [11]. Fitting the Time Of Arrivals (TOAs) obtained at Parkes lead to a timing solution with an phase with an rms residual of 90 μs throughout the LAT observations. Photon arrival times were referred to the Solar-System barycenter and pulse phases were assigned using the standard pulsar timing software TEMPO2 [7].

3 Vela pulse profile

In order to optimize the extraction of photons from the Vela pulsar, we adopt an energy-dependent Region Of Interest (ROI), defined by an angle $\theta <$ Max[1.6 $-$ 3Log10(EGeV), 1.3] degrees from the pulsar position. This includes a larger fraction of the PSF at high energies, where the background is relatively faint. We use the $Diffuse$ class events, those reconstructed events having the highest probability of being photons. Using such a cut we collect 32,400±242 pulsed photons and 2780±53 background photons with measured energy $>$ 0.03 GeV. Fig. 1 shows the 0.1-10GeV pulse profile from this energy-dependent cut using variable-width bins of 200 counts in order to highlight fine structures. From this light curve it is possible to see two main asymmetric peaks P1 and P2, respectively at phases $\phi = 0.130 \pm 0.001$ and $\phi = 0.562 \pm 0.002$. The outer edges of the two peaks had consistent Lorentzian half-widths of $\phi = 0.012 \pm 0.001$, while the falling edge of P1 has a Lorentzian half width of $\phi = 0.017 \pm 0.0015$, while the rising edge of P2 has a width $\phi = 0.027 \pm 0.005$. Thanks to the large energy range of the LAT, we can build energy-dependent light curves in order to see the evolution of the pulse shape with energy, as shown in 1. The main feature that can be distinguished is a decrease of P1 relative to P2 with increasing energy; P1 is not detectable above $\sim$ 10GeV. This confirms a trend seen in the EGRET data for the Crab, Vela and Geminga pulsars. The second pulse dominates at the highest energies, while interestingly at the lower energies, below $\sim$ 120MeV, the trend is reversed with P1 weakening again with respect to P2, with no statistically significant evidence for shifts in the phases of the P1 and P2 pulse components with energy. The next important feature is a distinct third peak at E $>$ 1 GeV (P3) at ϕ 0.27 in the 3-10GeV band, which is

[a] Assuming a neutron star moment of inertia $I_{45} = 10^{45}$ g cm^2

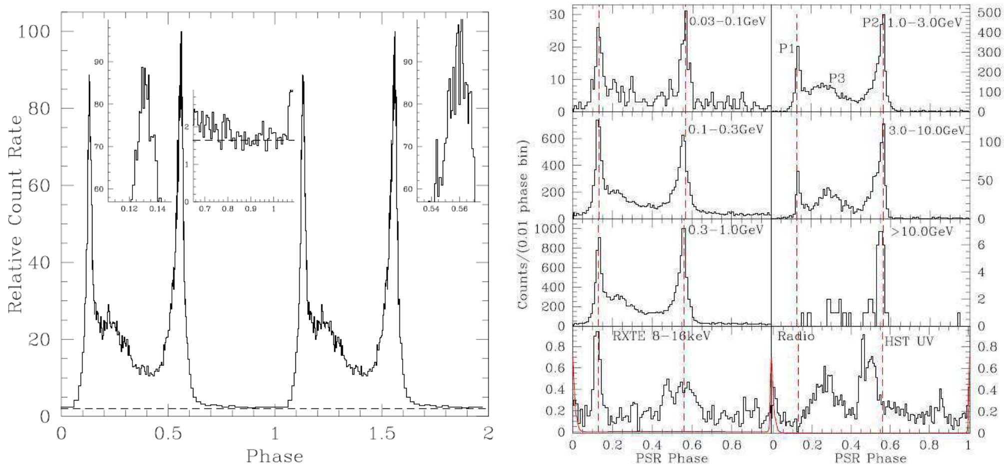

Figure 1: Right: Vela pulsar light curve for E 100 MeV. The dashed line shows the background level, as estimated from a surrounding annulus during the off-pulse phase. Insets show the pulse shape near the peaks and in the off-pulse region. Left: Energy-dependent light curve of the Vela pulsar, compared with X-rays and UV light curve. Each LAT pulsar profile is binned to 0.01 of pulsar phase, and dashed lines show the phases of the P1 and P2 peaks determined from the broad band light curve.

shifting in phase by $\delta\phi \sim 0.14$ between 0.2 and 15GeV and is present in the shoulder of P1 at E $<$ 1 GeV. Comparing with lower energies, we show also in Fig. 2 the 8-16 keV non-thermal X-ray pulse measured by RXTE [5] and the 4.1-6.5 eV NUV HST STIS/MAMA pulse profile [10]. Comparing those with the gamma-ray profile, we note that P1 is dominant in the non-thermal X-rays, while it is absent in the optical/UV, but pulse profiles at these energies have a strong peak in the bridge region at $\phi \sim 0.25$, well matched in phase to the P3 structure in the GeV pulse profiles.

4 The spectrum of the Vela pulsar

We studied the phase-averaged spectrum of Vela using a standard maximum-likelihood spectral estimator, provided with the Fermi SSC science tools. This fits a source model to the data, along with models for the isotropic (instrumental and extragalactic) and structured Galactic backgrounds, comparable with pre-launch simulation [1]. The basic model is a simple power law with exponential cutoff. With the large number of events collected for Vela, the statistical errors are very small, while systematic errors are still under investigation and we adopt conservative estimates of the systematic uncertainty in the LAT effective area, derived from the on-orbit estimation of the photon selection efficiency as function of energy and offaxis angle. This varies from $<$ 10% near 1 GeV to as much as 20% for energies below 0.1 GeV and 30% for energies greater than 10 GeV. The fit results is:

$$\frac{dN}{dE} = (2.08{\pm}0.04{\pm}0.13){\times}10^{-6} E^{-1.51\pm0.01\pm0.07} \exp[-(E/(2.857{\pm}0.089{\pm}0.17 GeV))^{b}] ph/cm^{2}/s/GeV \quad (1)$$

The first errors are the statistical values for the fit parameters, while the second errors are our propagated systematic uncertainties. The results have been compared using 3 different methods: a standard XSPEC analysis with our best model response matrices, a binned maximum likelihood estimator which computes the on-pulse photon counts in a point source weighted aperture in excess of off-pulse background counts (ptlike) and a method which propagates the model spectrum through simulated instrument response to compare with observed pulsed source counts. The resulting spectrum is shown in Fig. 2 as E^2 dN/dE along with this best fit model. In Fig. 2 we show also the EGRET points [8]: some studies have indicated that the EGRET response

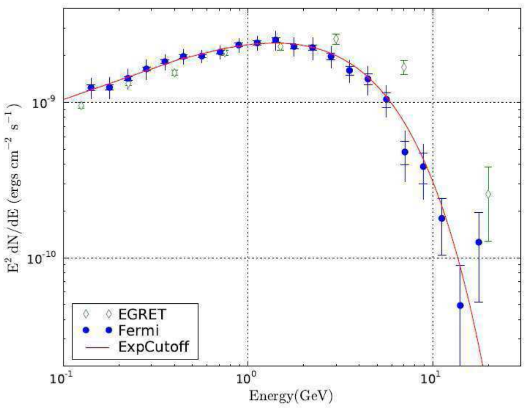

Figure 2: The phase-averaged Vela spectral energy distribution, with statistical (capped) and systematic (uncapped) errors depicted. EGRET data points are shown for comparison. The curve is the best-fit power law with a simple exponential cut-off.

was incorrectly estimated and this could explain the discrepancy with our data [2]. Trying to fix with a free exponential index b gives us an exponential index b = $0.88 \pm 0.04^{+0.24}_{-0.52}$ so that models with a hyper-exponential behavior are well excluded and the spectrum is fully consistent with the simple exponential b = 1 cut-off.

5 Conclusions

We present here some highlight of the main results coming from the early observation of the Vela pulsar by the LAT [2]. The observation performed during the calibration and instrument tuning and during the first months provided a large amount of photons much higher than previous missions. The analysis of the pulse profile with energy confirmed the trend of the ratio P1/P2 and provided the evidence of a third peak at high energies, which shifts in phase with energy. The study of the phase averaged spectrum show for the first time a full coverage of the energy cutoff, that has been modeled as an exponential cutoff, providing a strong constraint favoring the outer magnetosphere emission models. In order to better use Vela pulsar as a tool for constraining theoretical models, is thus necessary to collect more data and study the detailed evolution of the spectrum with the phase.

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