Fermi-LAT observations of the Vela X region

Marianne Lemoine-Goumard*† and Marie-Hélène Grondin*†
on behalf of the *Fermi*-LAT Collaboration and the Pulsar Timing Consortium

CNRS/IN2P3, Centre d'Études Nucléaires Bordeaux Gradignan, UMR 5797, Gradignan, 33175, France
†*Université de Bordeaux, Centre d'Études Nucléaires Bordeaux Gradignan, UMR 5797, Gradignan, 33175, France*

***Abstract*. The Vela supernova remnant (SNR) is the closest SNR to contain a young active pulsar, PSR B0833-45. The remnant spans about 8° in diameter and contains regions of non-thermal emission in the radio, X-ray and gamma-ray bands, including Vela X, a pulsar wind nebula (PWN) spanning a region of $2^\circ \times 3^\circ$ south of the pulsar. With a center offset by about 40' from the pulsar, Vela X served as the first prototype for offset PWN as a result of SNR expansion into an inhomogeneous medium; it emits in the radio, X-ray, and TeV gamma-ray bands. Using recent observations by *Fermi*-LAT, we have conducted a detailed study of the off-pulse emission in the region of the Vela pulsar. We will describe the *Fermi*-LAT measurement of this region and discuss the origin of the detected gamma-rays.**

***Keywords*: Gamma-rays, *Fermi*, Pulsar wind nebulae, Vela X**

I. Introduction

The region surrounding the Vela SNR ($\sim 8^\circ$ in diameter) is very well studied across the electromagnetic spectrum and contains a number of complex objects, including the pulsar PSR B0833-45 and the SNR RX J0852.0-4622. Located at a distance of $\sim$ 290 pc [5], it is the closest SNR to contain an active pulsar, PSR B0833-45, which is bright ($S_{1.4}\,\mathrm{GHz} \approx 1.5\,\mathrm{Jy}$), young (characteristic age $\tau_c = P/2\dot{P} = 11\,\mathrm{kyr}$), and energetic ($\dot{E}_{SD} = 6.9\times10^{36} I_{45}\,\mathrm{ergs/s}$, for a neutron star moment of inertia $10^{45} I_{45}\,\mathrm{g\,cm^2}$).

The SNR contains several regions of non-thermal emission, including those labelled by Risbeth el al. (1958) from radio observations as Vela X, Vela Y and Vela Z [11]. Vela X is the most prominent radio feature with the characteristic of having an almost flat radio spectrum. Further insight into the nature of Vela X was revealed by the detection of a diffuse X-ray emission extending south of the Vela pulsar by *ROSAT* [10]. This feature was first interpreted as an X-ray jet from the pole of the pulsar along which the pulsar loses energy. However, Chandra observations showed that this X-ray emission (called "cocoon") lies along the extension of the pulsar equator. An alternate explanation for the X-ray filament was then proposed by Gvaramadze (1999) who suggested that this feature represents a projection effect of a Rayleigh-Taylor instability, which is caused by the impact of the SN ejecta with the wind-driven shell from the progenitor [6].

Though the cocoon is no longer considered as a jet, it deserves further investigation and is important in different perspectives. Indeed, a conclusive proof for the existence of relativistic particles in the X-ray cocoon was revealed by H.E.S.S. observations of the Vela region with an integral flux above 1 TeV of $\sim$50% of that of the Crab Nebula [2]; this places Vela X as one of the best PWN candidate for *Fermi*. Also, it was the first middle-aged pulsar wind nebula (PWN) to be detected and served as the first prototype for offset PWN as a result of SNR expansion into an inhomogeneous medium [3]. With the successful launch of the *Fermi* Gamma-ray Space Telescope on June 11, 2008, we have a new opportunity to study the Vela X region in the high-energy γ-ray band.

II. *Fermi*-LAT Observations

The initial observations of the Vela pulsar were based on 35 days of on-orbit verification and the initial $\sim$ 40 days of the on-going first year sky survey. We report here the results based on these initial observations even though the survey observations keeps increasing the photon statistics accumulated from the Vela region. More details on these observations can be found at [1]. 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.

III. Radio Timing

The Vela pulsar is the brightest persistent point-source in the γ-ray sky with pulsed photons observed up to 17 GeV. The study of Vela X thus imply to assign a phase to the γ-ray photons and select the off-pulse ones. Since the Vela pulsar is young and exhibits substantial timing irregularities, 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 for pulsar monitoring in support of the *Fermi* mission [12]. A total of 27 times-of-arrival (TOAs) were obtained at a frequency of 1.4 GHz over the period of the LAT observations. No large timing irregularities or glitches were detected. An accurate determination of the pulsar's dispersion measure of $67.95{\pm}0.03\,\mathrm{cm}^{-3}\mathrm{pc}$ was obtained by measuring the delay in the TOAs of the pulse across the 256 MHz bandpass of the 1.4 GHz receiver. This allows extrapolation of the radio ephemeris to infinite frequency with an error of $\sim$60 μs. Photon arrival times were referred to the Solar-System barycenter and pulse phases were assigned using the standard pulsar timing software TEMPO2 [7].

IV. Results

Using "Diffuse" class events (those reconstructed events having the highest probability of being photons) contained in an energy-dependent region of interest defined by an angle $\theta < \mathrm{Max}[1.6 - 3\mathrm{Log}_{10}(E_{\mathrm{GeV}}), 1.3]$ deg from the pulsar position, we collect $32,400 \pm 242$ pulsed photons and $2,780 \pm 53$ background photons with energy $>$ 0.03 GeV. Fig. 1 shows the 0.1-10 GeV pulse profile from this energy-dependent cut using variable-width bins of 200 counts in order to highlight fine structures. From this pulse profile, we determine the off-pulse region ($\phi = 0.65 - 1.05$) and present an inset of this phase interval with 50 counts/bin in Fig. 1. We see that, as for other non-radio Vela pulse profiles, there is a faint tail of pulsed emission in this region, reaching non-detectability only near $\phi = 0.8 - 1.0$. We estimate that this 'off pulse' window contains 235±15 pulsed photons (7.3×10^{-3} of the pulsed flux). It is clear from this Figure that the Vela region is strongly dominated by the pulsed emission except in the off-pulse interval.

Figure 2 presents *Fermi* γ-ray images of the Vela pulsar in three energy bands in the LAT range separated into the on- ($\phi = 0.05 - 0.65$) and off- ($\phi = 0.65 - 1.05$) pulse phase regions. The images (except for the low count high energy off-pulse frame) are smoothed by Gaussians (with $FWHM = 1.2°$, $0.7°$ and $0.2°$ for the low to high energy images, respectively). The off-pulse images show the bright diagonal band of the Galactic diffuse emission, with appreciable structure. While a clump of extended emission surrounds the pulsar position on the few degree scale, it is at present not possible to associate this flux with known Vela PWN structures (e.g. the Vela-X TeV PWN, contours in the middle energy band).

As a first attempt at constraining unpulsed (e.g. PWN) emission from Vela we have attempted to fit for a point source in the off-pulse phase window, fixed at the position of the pulsar. Using 0.1–10 GeV photons in an $8°$ ROI in the $\phi = 0.65 - 1.05$ phase interval, we derive a 95% CL upper limit on the flux of $1.8 \times 10^{-7} \gamma/\mathrm{cm}^2/\mathrm{s}$. After subtracting the estimated remnant pulsed flux in this window (0.73% of the phase-averaged flux) and scaling to the full pulse phase, this provides a limit on an unpulsed point source at the position of Vela of 2.8% of the $E > 100$ MeV pulsed emission count-rate. Additional survey data (September 2008 to May 2009) are currently analysed, especially at higher energy, to search for a resolved PWN correlated with the TeV or radio structures.

V. Discussion and Conclusion

Different scenarios have been proposed to interpret the multi-wavelength data accumulated on Vela X.

Horns et al. (2006) proposed a hadronic model wherein the γ-ray emission is the result of the decay of neutral pions produced in proton-proton collisions in the cocoon. However, this model requires a density larger than 0.6 cm^{-3} which seems disfavoured by recent XMM observations [9]. La Massa et al. (2008) proposed a leptonic model with radio and X-ray emissions resulting from synchrotron radiation and γ-ray emission arising from Inverse-Compton scattering. In this model, the authors need a 3-component broken power-law to describe the electron population and adequately fit the data [9]. A single break model can also reproduce the multi-wavelength data if a separate electron population produces the radio emission [4]. In this latter case, the morphology of the γ-ray emission observed by *Fermi* would be very similar to the radio one since it would be produced by the same electron population.

Here, we have shown that, in the off-pulse phase, a clump of extended emission surrounds the pulsar position on the few degree scale but it is not possible at this time to firmly associate those photons with Vela X. An upper limit, assuming a point-source at the position of the pulsar, was derived which already constraint the parameters of the emission models cited above, such as the magnetic field or the electron population. The additional survey data whose analysis is still ongoing will allow us to do a complete morphological analysis, thus providing further insights on the electron population.

VI. Acknowledgment

The *Fermi*-LAT Collaboration acknowledges support from a number of agencies and institutes for both the development and operation of the LAT as well as the scientific data analysis. These include NASA and the DOE in the United States, the CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K.A. Wallenberg Foundation, the Swedish Reseacrh Council and the National Space Board in Sweden. Additional support from INAF in Italy for science analysis during the operations phase is also gratefully acknowledged.

The Parkes radio telescope is part of the Australia Telescope which is funded by the Commonwealth Government of operation as a National Facility managed by CSIRO. We thank our colleagues for their assistance with the radio timing observations.

References

[1] Abdo, A. A, et al. (*Fermi*-LAT Collaboration), 2009, ApJ, 696, 1084

[2] Aharonian, F. A., et al. (H.E.S.S. Collaboration) 2006, A&A, 448, L43

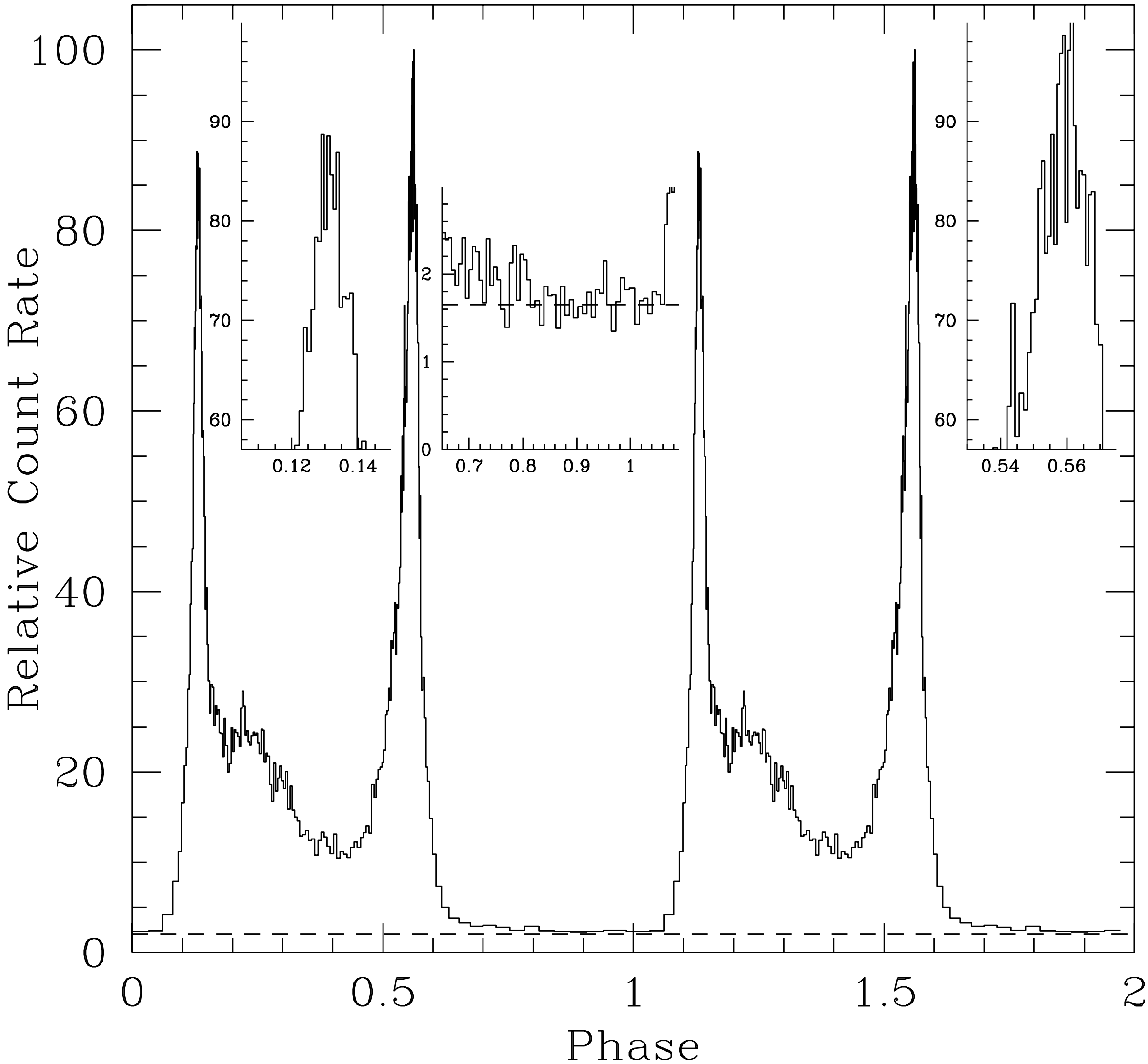

Fig. 1: Vela broad band ($E = 0.1 - 10\,\mathrm{GeV}$) pulse profile for all photons from an energy dependent ROI. Two pulse periods are shown. The peak of the radio pulse is at phase $\phi = 0$. The count rate is shown in variable width phase bins with a constant number of counts. The dashed line shows 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.

[3] Blondin, J. M., Chevalier, R.A. & Frierson, D.M. 2001, ApJ, 563, 806
[4] De Jager, O. C., Slane, P. O., LaMassa S. M., 2008, ApJL, 689, L125
[5] Dodson, R. et al. 2003, ApJ, 596, 1137
[6] Gvaramadze, V. 1999, A&A, 352, 712
[7] Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655
[8] Horns, D., Aharonian, F. A., & Santangelo, A., 2006, A&A, 451, L51
[9] LaMassa S. M., Slane, P. O., & De Jager, O. C., 2008, ApJ, 689, L121
[10] Markwardt, C. B. & Ögelman, H. B. 1995, Nature, 375, 40
[11] Risbeth, H. 1958, Aust J. of Phys., 11, 550
[12] Smith, D. A. et al. 2008., A&A, 492, 923

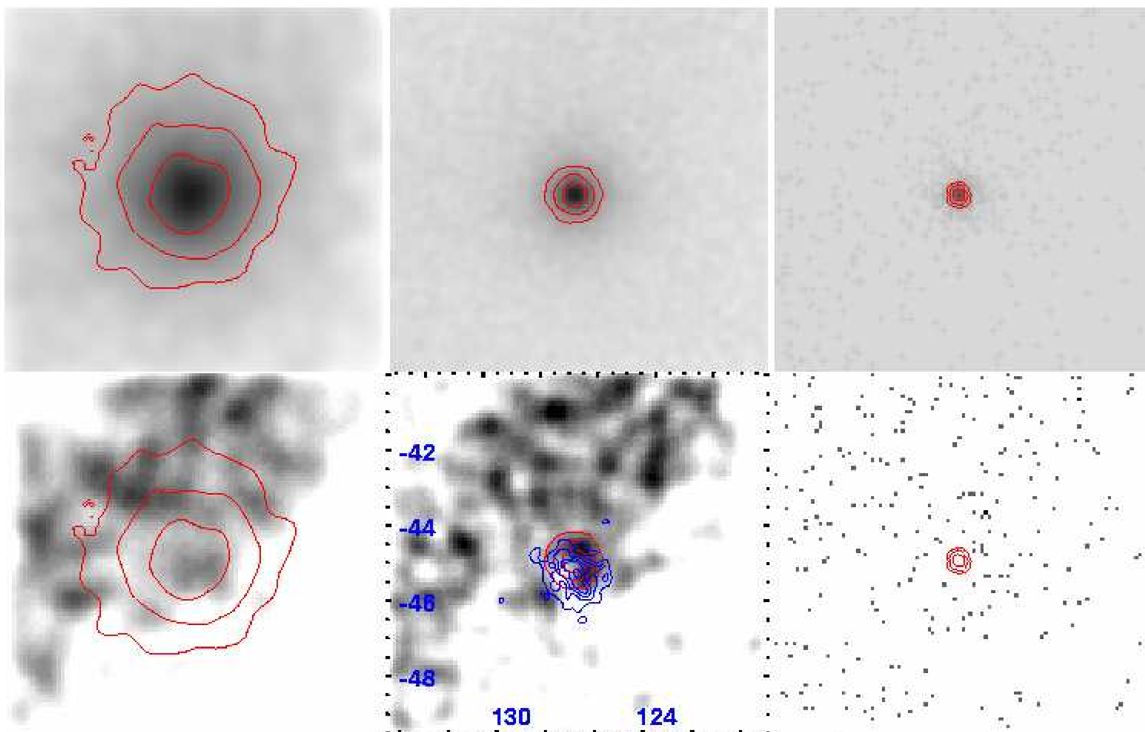

Fig. 2: On- ($\phi = 0.05 - 0.65$, top row) and off- ($\phi = 0.65 - 1.05$, middle row) pulse phase images in three energy bands. Each panel spans $10^\circ \times 10^\circ$ in equatorial coordinates centered on Vela (RA and Dec marked in degrees in the central panel). On-pulse data are dominated by the point source; the panels have a hard square root stretch to show the faint wings of the PSF. The off-pulse images (linear grey scale) are dominated by Galactic diffuse emission; some of the structure is due to limited count statistics. Contours of the point source at 0.5, 0.25 and 0.125 of the peak intensity are shown (red) in each frame. In the middle energy off-pulse image we also show the HESS Vela PWN contours (Aharonian et al. 2006; blue).