Observations of the Crab Pulsar with VERITAS

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The *Fermi* space telescope has detected over 100 pulsars. These discoveries have ushered in a new era of pulsar astrophysics at gamma-ray energies. Gamma-ray pulsars, regardless of whether they are young, old, radio-quiet etc, all exhibit a seemingly unifying characteristic: a spectral energy distribution which takes the form of a power law with an exponential cut-off occurring between ∼1 and ∼10 GeV. The single known exception to this is the Crab pulsar, which was recently discovered to emit pulsed gamma rays at energies exceeding a few hundred GeV. Here we present an update on observations of the Crab pulsar above 100 GeV with VERITAS. We show some new results from a joint gamma-ray/radio observational campaign to search for a correlation between giant radio pulses and pulsed VHE emission from the Crab pulsar. We also present some preliminary results on Lorentz invariance violation tests performed using *Fermi* and VERITAS observations of the Crab pulsar.

1. Introduction

The *Fermi* space telescope has detected over 100 new gamma-ray pulsars, the bulk of which are young, high-$\dot{E}$, pulsars. These discoveries have ushered in a new era of research into pulsars and the physics of emission from pulsar magnetospheres. However, despite the wealth of new data in recent years, the decades-old problem of the origin of gamma-ray emission from pulsars remains unsolved. The origin of the coherent radio emission from pulsars is also poorly understood, as are the exotic temporal phenomena of *Nulling* and *Giant Radio Pulses* (GRPs) exhibited by some radio pulsars.

In spite of the difficulty faced to explain the emission from pulsars, their regular and predictable pulsations and immense density makes them incredibly useful laboratories for the study of space-time and gravitation. In this contribution, we present an update on observations of the Crab Pulsar above 100 GeV with the Very Energetic Ray Imaging Telescopes Array System (VERITAS). In particular, we focus on a recently completed study to search for a correlation between the emission of GRPs and pulsed very-high-energy (VHE) gamma-ray emission and preliminary results from a study searching for the effects of quantum gravity on the propagation of photons of different energies over large distances.

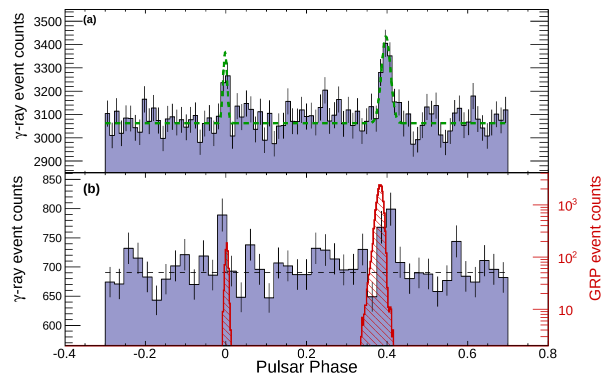

Figure 1: Panel (a) shows the VHE gamma-ray pulse profile ($E_\gamma > 120$ GeV) of Crab pulsar measured by VERITAS (see Aliu et al. [2011]). The overlaid (green) curve was determined from a maximum likelihood fit to the unbinned VERITAS data. Panel (b) shows the VERITAS (blue) and GRP (red) profiles for 11.6 hours of simultaneous VERITAS/GBT observations.

2. Searching for a VHE-GRP Correlation

2.1. GRPs in the Crab Pulsar

The Crab pulsar, PSR B0531+21, is a powerful young pulsar and is, so far, the only pulsar to be detected above 100 GeV [Aliu et al. 2011, Aleksić et al. 2012]. The Crab pulsar is also one of only several known pulsars exhibiting the phenomenon of giant radio pulse [Knight 2006]: single radio pulses with flux densities that greatly exceed the average pulse flux density. GRPs appear in the same phase range as normal radio pulses, but their energy distribution is a power-law [Cordes et al. 2004, Popov & Stappers 2007] in contrast to the regular pulses that follow a Gaussian or log-normal distribution [Burke-Spolaor et al. 2012]. In the Crab pulsar, individual GRPs can be a few nanoseconds to a few microseconds wide [Hankins et al. 2003] and can, at their maximum, be as bright as a few million Janskys [Soglasnov 2007].

Above 6 GHz, stark differences in the behaviour of main pulse GRPs and interpulse GRPs have been observed in the Crab pulsar. Interpulse GRPs are typically several microseconds long and populate a set of regularly spaced frequency bands [Hankins & Eilek

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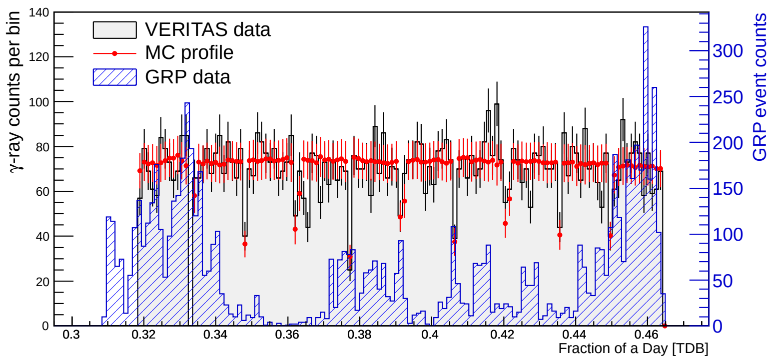
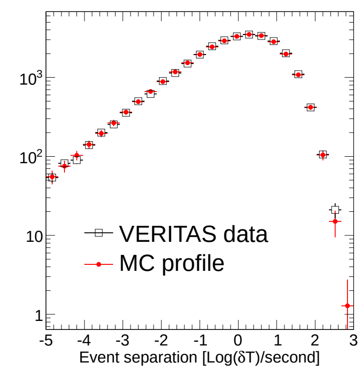


(a) Event Arrival Times



(b) Event Separation

Figure 2: This figure shows examples of the match between the VERITAS data and the Monte-Carlo model. The event rate distribution is shown on the left and the arrival time event-separation distribution for each pair of consecutive events is shown on the right.

2007] in contrast to main pulse GRPs which exhibit broadband spectra and appear as a succession of narrow pulses ranging from unresolved widths below 0.4 ns to widths of a few microseconds. In the model of Lyutikov [2007], the band structure seen in the Crab pulsar interpulse GRPs at high frequencies is generated by particles in the outer pulsar magnetosphere which have been energised by a magnetic field reconnection and emit via anomalous cyclotron resonance. A prediction of this model is the existence of a particle beam in the outer magnetosphere with a large Lorentz factor, $\mathcal{O}(10^8)$, which should generate curvature photons with energies as high as tens of GeV. The mechanisms responsible for the generation of GRPs are, however, still largely unknown. Changes in the coherence of the plasma beam, which is believed to be responsible for the normal pulsed radio emission, can in principle explain the generation of GRPs. Such coherence changes will, however, have no effect on the incoherent emission from pulsars (optical, x-ray, gamma-ray). Mechanisms which increase the rate of particle production within the magnetospheric emission region, or which change the direction of the emission beam can, in principle, affect the higher energy incoherent emission and may create an enhancement in the gamma-ray emission.

Several previous studies have been performed to search for a possible connection between GRPs in the Crab and higher-energy incoherent emission. While only upper-limits have been report at x-ray (1.4-4.5 keV) [Bilous et al. 2012] and gamma-ray (50-220 keV and 0.1-5 GeV) [Bilous et al. 2011, Lundgren et al. 1995] energies, Shearer et al. [2003], observed a significant 3% enhancement in the optical main pulse concurrent with the period of emission of GRPs measured at 1380 MHz. No enhancement was seen in the interpulse. This observation suggests a link between coherent radio emission and incoherent optical emission in the Crab pulsar. Small changes in the pair-creation rate leading to localised density increases within the emission plasma could create the GRP event and provide a small enhancement in the optical incoherent emission.

2.2. Observations and Search Strategy

VERITAS and the 100-m Robert C. Byrd Green Bank Telescope (GBT) simultaneously observed the Crab pulsar for a total of 11.6 hours across four nights in December 2008 and November and December 2009. A total of 15366 GRP radio events recorded at 8.9 GHz, whose peak signal-to-noise ratio was at least seven times greater than the average radio signal, were selected for the correlation study (see Figure 1). The VERITAS observations were made at high elevation ($El > 70°$) under the best possible sky conditions with the four telescopes fully operational and with a GPS time-stamp event tagging error < 10 μs. The VERITAS event reconstruction and cosmic-ray rejection followed the identical procedure as described in [Aliu et al. 2011]. The GPS time of the candidate gamma-ray events which passed analysis cuts was converted to barycentric dynamical time and phase-folded using the Crab pulsar monthly timing ephemeris[1] [Lyne et al. 1993].

Using the VERITAS and GRP photon lists a correlation analysis was performed. VERITAS events were selected if their barycentric arrival time was within a time window positioned around the GRP arrival times. Gamma-ray enhancements which lagged, lead or were contemporaneous with the GRP were investigated. Since the correlation length is unknown (if a correlation exists at all), eight different coincidence

[1] http://www.jb.man.ac.uk/pulsar/crab.html

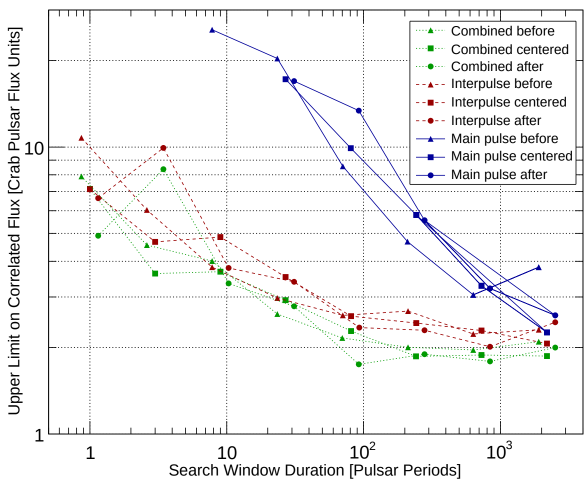


Figure 3: 95% confidence level upper limit on the VHE gamma-ray flux correlated with GRPs. The slight negative and positive shift of the x-position of the *before* and *after* symbols is done as a visual aid. Limits are given in units of the average VHE pulsar flux measured by VERITAS [Aliu et al. 2011].

time windows were chosen lasting; 1, 3, 9, 27, 81, 243, 729 and 2187 pulsar rotations. Main pulse and interpulse GRPs were also considered separately, thus 72 different correlation searches were performed. A Monte-Carlo model of the VERITAS data was used to determine the number of coincident VHE events expected in the absence of a correlation. Monte-Carlo time series data sets were generated by drawing random times from the raw VERITAS trigger rate histograms. A random subset of these events was chosen to contain the temporal signature of the pulsar with phase values draw from the functional form which describes the shape of the pulse profile of the Crab pulsar as measured by VERITAS (see the dashed curve in panel (a) in Figure 1). This procedure was used to generate sets of Monte-Carlo data which contain a signal from the Crab pulsar at a chosen flux level and which model all the data rate characteristics of the real VERITAS data. Examples of the match between the Monte-Carlo time-series datasets and the VERITAS gamma-ray data are shown in Figure 2.

2.3. GRP-VHE Correlation Results

No significant enhancement in VHE gamma-ray emission correlated with GRPs measured at 8.9 GHz was observed in any of the 72 searches performed. Using the Monte-Carlo model of the Crab pulsar signal within the VERITAS data, it is possible to investigate the probability that a given number of correlated events is consistent with a chosen level of correlated VHE enhancement. Following a similar procedure as Bilous et al. [2011], the 95% confidence level upper-limit on the enhanced VHE emission correlated with GRPs was calculated for each of the 72 searches performed. These upper limit values are shown in Figure 3.

These findings agree with results previously reported at keV and GeV energies [Bilous et al. 2011, 2012, Lundgren et al. 1995]. GRP-emission mechanisms associated with changes in plasma coherence will not cause enhancements in incoherent emission, while small and localised changes in the pair-creation rate can explain the small (3%) optical-GRP correlation seen by Shearer et al. [2003] but yield VHE enhancements below the current VHE sensitivity. In recent models of pulsed VHE emission from the Crab pulsar [Aharonian et al. 2012, Lyutikov et al. 2012] any expected GRP-VHE enhancements are also below the sensitivity of current VHE instruments.

See Aliu et al. [2012] for a detailed description of this VHE-GRP correlation study.

3. Searching for Quantum Gravity

Many theoretical investigations aim to formulate a theory of quantum gravity in order to unify the theories of quantum mechanics and general relativity. Some approaches to the theory of quantum gravity result in equations of motion which contain an energy dependent dispersion relation for massless particles, meaning that the speed of light in a vacuum would not be constant. Such theories would violate Lorentz invariance. Depending on the particular framework, photons would travel a the speed

$$\nu(E) = c\left[\ 1 \pm \left(\frac{E}{E_{QG}}\right)^n\ \right] \tag{1}$$

where E is the photon energy and E_{QG} is the energy scale at which the effects of quantum gravity become important [Amelino-Camelia et al. 1998]. The order, n, of the energy dependence, and the $\pm$ sign ambiguity would be fixed within the framework of a given model for quantum gravity. To search for these dispersive quantum gravity effects one can apply the following framework:

- Two photons with energies E_1 and E_2 emitted simultaneously arrive at an observer at a distance, L, with time separation, Δt.

- Depending on the order n of the energy dependence, the time difference Δt for the linear and the quadratic terms in (E/E_{QG}) are:

$$\Delta t_1 = \frac{L}{c}\frac{E_2 - E_1}{E_{QG}} \Rightarrow E_{QG} = \frac{L}{c}\frac{E_2 - E_1}{\Delta t_1} \tag{2}$$

and

$$\Delta t_2 = \frac{L}{c}\frac{3}{2}\frac{E_2^2 - E_1^2}{E_{QG}^2} \Rightarrow E_{QG} = \sqrt{\frac{L}{c}\frac{3}{2}\frac{E_2^2 - E_1^2}{\Delta t_2}} \quad (3)$$

- By measuring the structure in a temporal event, such as an emission flare, in different energy bands, we can place an upper limit on Δt.
- By placing a limit on the maximal Δt, a lower bound on E_{QG} can be found.

From Equations 2 and 3 it is clear that when searching for Lorentz invariance violation (LIV) it is favorable to observe temporal phenomena which occur on short time scales (minimising Δt) at a large distance from the observer (maximising L) over a wide photon energy range (maximising $E_2 - E_1$). Gamma-ray bursts (GRBs) and TeV gamma-ray flares from active galactic nuclei (AGN) meet all of the above criteria, and to date, have been used to place the strongest limits on the energy scale of quantum gravity [H.E.S.S. Collaboration et al. 2011, Abdo et al. 2009].

3.1. LIV with Gamma-ray Pulsars

Kaaret [1999] showed that gamma-ray pulsars were also excellent tools for LIV searches and achieved a lower limit on the energy scale of quantum gravity of 1.8×10^{15} GeV for case of $n = 1$ (Equation 2). Further, doing LIV tests with gamma-ray pulsars has several benefits over flaring transients such as GRBs or AGNs:

- Tests do not rely on random transient events and observational luck.
- Limits improve with longer exposures.
- Limits are based on highly significant measures of peak positions rather than on a handful of single photons.
- Delay effects intrinsic to the source can be distinguished from LIV effects.
- If a delay effect is measured, the delay separation will appear as a constant phase offset as the pulsar period lengthens, if it's a source effect.
- If a delay effect is measured and is caused by LIV, this effect should stay constant in time as the pulsar slows and so should shift in phase by the amount $\Delta\Phi(t) = \Delta t/(P + t\dot{P})$.

Following the recent detection of the Crab pulsar by VERITAS, which has extended the observed energy range of the pulsar by over an order of magnitude, we are prompted to repeat the LIV test performed by Kaaret [1999].

3.2. Preliminary Results

Using the VERITAS and *Fermi* Crab pulse profiles shown in Figure 4 we can place a limit on E_{QG}. The positions of the emission peaks are consistent within measurement uncertainty. The measurement of the VERITAS emission peak positions, which was determined from an unbinned maximum likelihood fit to the VERITAS phase data (solid line plotted in Figure 4), is the dominant source of uncertainty. This uncertainty is about 2×10^{-3} phase units, or, 60 μs. Using the 95% confidence level upper limit on the time separation between the peaks, 100 μs, the canonical distance to the Crab pulsar of 2 kpc, and the conservative value of 120 GeV for the difference between the *Fermi* and VERITAS energy ranges, we arrive at 3×10^{17} GeV and 7×10^{9} GeV for the lower limit on the values of E_{QG} for the liner and quadratic case, respectively.

4. Conclusion

VERITAS is engaged in a broad and varied pulsar observation campaign. These proceedings present a summary of two research lines on the Crab pulsar which have recently been, or are soon to be, completed. These include the first limits on the level of enhanced VHE emission correlated with GRPs in the Crab pulsar. Given the level of uncertainty in theories of GRP emission, it is hard to draw firm conclusions resulting from the lack of any observed correlation with VHE emission. We are not aware of any theory with quantitative predictions of correlated emission between GRPs and VHE emission. Small and localised changes in the pair-creation rate, which can explain the small (3%) optical enhancements previously measured by Shearer et al. [2003], would yield VHE flux enhancements which are below our sensitivity.

We also present some preliminary limits on the energy scale of quantum gravity determined from VERITAS and *Fermi* observation of the Crab pulsar. These limits are only one order of magnitude lower than the best limits ever achieved (with GRBs and AGNs) and are set to improve with more data, more VHE pulsars, and improved analysis methods.

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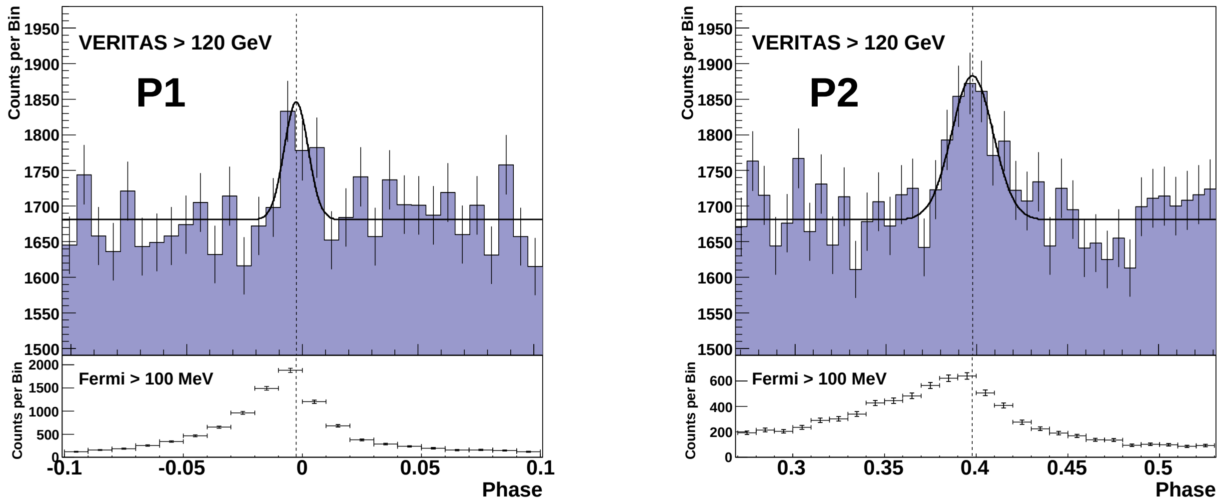

(a) Crab pulsar main pulse

(b) Crab pulsar interpulse

Figure 4: A zoom in of the Crab pulsar gamma-ray emission peaks [Aliu et al. 2011]. The full VERITAS profiles are shown in Figure 1. The overlaid curve is from a maximum likelihood fit to the unbinned VERITAS data. The *Fermi* points are taken from Abdo et al. [2010].

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