



Recent Pulsar Results from VERITAS on Geminga and the Missing Link Binary Pulsar PSR J1023+0038

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Abstract

In recent years, the *Fermi*-LAT gamma-ray telescope has detected a population of over 160 gamma-ray pulsars, which has enabled the detailed study of electromagnetic radiation from pulsars at energies above 100 MeV. Further, since the surprising detection of the Crab pulsar in very high-energy (VHE; $E > 100$ GeV) gamma rays by the MAGIC and VERITAS collaborations, there has been an ongoing effort in the astrophysics community to detect new pulsars in the VHE band. However, the Crab remains the only pulsar so far detected in VHE gamma rays, raising the question of whether or not the Crab is unique and also making it more difficult to constrain model predictions that attempt to explain the emission. Presented here are recent VERITAS results from observational campaigns on the brightest northern-hemisphere high-energy gamma-ray pulsar Geminga and the missing link binary pulsar PSR J1023+0038, which have both resulted in upper limits on a possible VHE flux. These limits are placed into context with the current theoretical framework attempting to explain the origin of the gamma-ray emission from pulsars. Additionally, future plans for pulsar observations with VERITAS will be briefly discussed.

VERITAS

The VERITAS array of four 12m diameter imaging atmospheric Cherenkov telescopes is located at the Fred Lawrence Whipple Observatory (FLWO) in southern AZ, USA. The telescope reflectors each consist of 345 hexagonal mirror facets, and the cameras comprise 499 photomultiplier tubes giving a total field of view of $\sim 3.5^\circ$. VERITAS is sensitive to gamma-rays in the range 0.85 to > 30 TeV with a sensitivity to detect a 1% Crab Nebula source in ~ 25 hr. It has an energy resolution of 15–25% and an angular resolution of 0.1° (68% containment) [1].

Introduction

There are now over 160 pulsars detected in the high-energy (HE; $E > 100$ MeV) gamma-ray band by the *Fermi*-LAT, which has greatly facilitated the study of their radiation. Spectral energy distributions (SEDs) of pulsars in gamma rays are typically well-characterized by a broad curvature radiation component followed by a spectral break at a few GeV and a subsequent exponential cut-off [2] (see Figure 1 for a typical pulsar SED). However, recently, two pulsars have been detected considerably above the HE spectral break. The Vela pulsar has been detected from the ground by H.E.S.S. above 30 GeV [Gajdus, M., these proceedings] and by the *Fermi*-LAT above 50 GeV [3], whereas the Crab pulsar has been detected in the VHE band by MAGIC [4] and VERITAS [5]. The combined SED of the Crab pulsar favors a power-law fit above ~ 10 GeV [5]. Whether or not the VHE emission from the Crab pulsar is unique with respect to the rest of the gamma-ray pulsar population remains to be seen.

Geminga

The Geminga pulsar is located at the nearby distance of ~ 200 pc and is the second-brightest steady HE gamma-ray source in the sky. The Geminga pulsar has a spin period of ~ 240 ms and a spin-down luminosity of 3.2×10^{34} erg s^{-1} [8]. The spectrum of Geminga above 100 MeV can be described by a power law with an exponential cut-off [2]; however, [9] have reported that the spectrum is better described by a power-law above the break energy.

PSR J1023+0038

PSR J1023+0038 is an eclipsing binary system located at a distance of 1370 ± 40 pc [10] containing a millisecond pulsar (MSP) with a fast spin period of 1.69 ms orbiting a companion star every ~ 5 hr [11]. This system has been caught in the act of “recycling” — switching between an LMXB state with an accretion disk to a radio MSP state [12]. The observed behavior of the so-called “missing-link” PSR J1023+0038 system has helped solidify the recycling scenario as the preferred explanation for the origin rapid rotation of MSPs.

Analysis & Results: Geminga

The VERITAS observational campaign on Geminga has resulted in the accumulation of a total of 71.6 hr of quality-selected data. Event arrival times are barycentered and phase-folded with T_{Tempo2} [14]. The phase-folded Geminga pulsar data recorded by the *Fermi*-LAT shows two emission peaks (P1 and P2), which are used to define phase regions of expected signal for the VHE gamma-ray data taken by VERITAS. The light curves are shown in Figure 2.

Upper limits (ULs) on excess counts for the P1 and P2 phase regions are computed at the 95% confidence level (CL) using the method of [15]. The ULs are converted to integral flux ULs above 135 GeV of 4.0×10^{-13} $\text{cm}^{-2} \text{s}^{-1}$ for P1 and 1.7×10^{-13} $\text{cm}^{-2} \text{s}^{-1}$ for P2. These ULs are shown along with a phase-averaged HE SED for the Geminga pulsar in Figure 3.

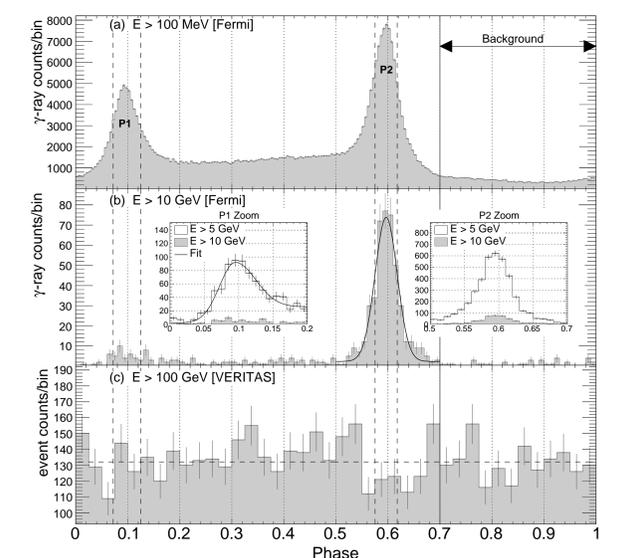


Figure 2: Phase-folded light curves for the Geminga pulsar for both *Fermi*-LAT (panels a and b) and VERITAS data (panel c). In panel a, the phase-folded light curve of the *Fermi*-LAT data with an energy threshold of 100 MeV is shown, and the region defined as background is indicated by the arrow. Panel b shows the data with an energy threshold of 10 GeV. Panel c shows the phase-folded VERITAS data from the location of the Geminga pulsar. The vertical dashed lines in all three panels represent the phase regions for P1 and P2. Figure from [13].

Analysis & Results: PSR J1023+0038

The search for pulsed VHE emission was split into two parts as VERITAS data were taken both before and after the 2013 June disappearance of the radio pulsar. The accumulated time on the target is 18.1 hr for the radio MSP state and 8.2 hr for the accretion/LMXB state. The *H*-Test [16] is used to test for the presence of a periodic signal in the data. The *H*-Test does not reveal any evidence for periodicity in the VHE phaseograms, which are shown in Figure 4. The *H* statistics are used to compute 2 and 3σ upper limits via the method of [17] above an energy threshold of 166 GeV assuming a duty cycle of 10% and Gaussian pulse shapes. The computed *H* statistics and pulsed flux ULs are shown below in Table 1.

J1023 State	<i>H</i> statistic	2σ pulsed VHE flux UL ($\text{m}^{-2} \text{s}^{-1}$)	3σ pulsed VHE flux UL ($\text{m}^{-2} \text{s}^{-1}$)
Radio MSP	0.28	6.16×10^{-9}	9.73×10^{-9}
Accretion/LMXB	0.18	1.12×10^{-8}	1.97×10^{-8}

Table 1: *H* statistics and integral pulsed VHE flux upper limits > 166 GeV for both states of PSR J1023+0038.

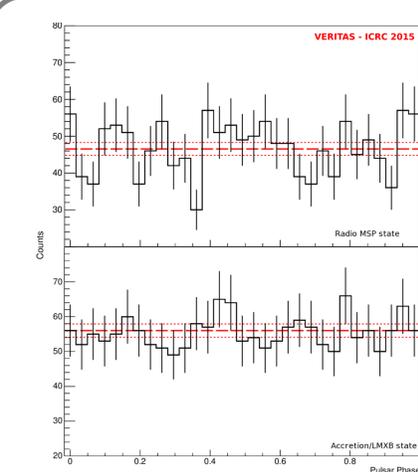


Figure 4: Phase-folded light curves of events recorded by VERITAS from the direction of PSR J1023+0038.

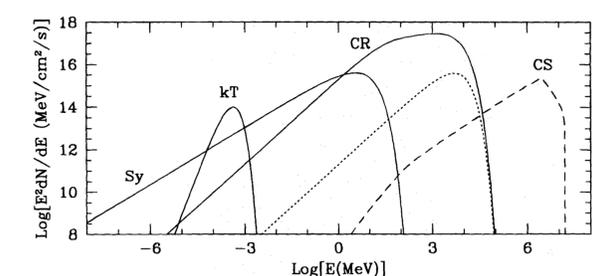


Figure 1: A typical multiwavelength SED for a pulsar. The solid line labeled Sy refers to the synchrotron component of the radiation, kT refers to a thermal emission component from the neutron star surface, CR denotes the signature of curvature radiation, and the dotted line labeled CS refers to potential Compton scattering in the magnetosphere. Figure reproduced from [7].

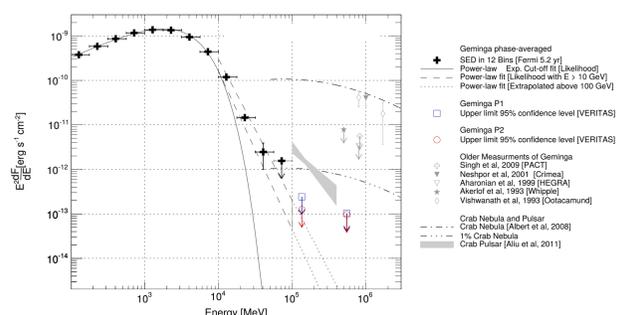


Figure 3: Phase-averaged SED for the Geminga pulsar with VHE flux ULs (open squares and circles) for the P1 and P2 phase regions computed from the VERITAS data. The energy thresholds for the two sets of VHE flux ULs are 135 and 550 GeV.

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