Pulsed VHE $\gamma$-ray Emission Constraints for PSR B1951+32 from STACEE Observations

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ABSTRACT

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a ground-based telescope which uses the wave-front-sampling technique to detect very high energy (VHE) gamma rays. STACEE’s sensitivity in the energy range near 100 GeV permits useful observations of pulsars with the potential to discriminate between various proposed mechanisms for pulsed gamma-ray emission.

We present results from observations of PSR B1951+32 taken during the 2005 and 2006 observing seasons. Based on 12.5 hours of data we derive an upper limit on the pulsed emission from PSR B1951+32 and discuss the implications of our result for understanding pulsar emission mechanisms.

Subject headings: gamma ray: observations — pulsars: individual(PSR B1951+32)
1. Introduction

Pulsars were discovered in 1967 using a radio telescope at Cambridge University (Hewish & Bell 1968). Subsequent investigations identified pulsars with neutron stars and revealed that the pulsed emission arises as the emission region of the rotating neutron star periodically points toward Earth. The number of known pulsars detected at radio wavelengths exceeds 1500 with around 70 of these seen in X-rays (Manchester et al. 2005; Kaspi et al. 2006). Additionally, the EGRET instrument on board the Compton Gamma-Ray Observatory strongly detected six pulsars emitting photons above 100 MeV (Crab, Geminga, Vela, PSR B1951+32, PSR 1706-44 and PSR 1055-32) (Nolan et al. 1996) and found a marginal signal from a seventh pulsar (PSR B0656+14) (Ramanamurthy et al. 1996).

However, more than forty years of research have not determined the mechanism(s) producing the pulsed radio through gamma-ray emission. In particular, three different general classes of models have been offered to explain how pulsars generate X-rays and gamma rays. All three models trace back to early standard magnetospheric models of neutron stars (Goldreich and Julian 1969). Basically, as the neutron star rotates, its intense magnetic causes large electrical potentials which pull charged particles away from the surface of the star. Except for a few locations, these particles distribute themselves in such a way so as to short out the large electric fields. Those locations where the fields are not shorted out accelerate the charged particles which subsequently produce curvature and synchrotron radiation as they follow the magnetic field lines. The charged particles will scatter lower energy photons to produce high-energy gamma rays via the inverse-Compton process.

The three most popular models argue for different locations where the electric fields are produced. Consequently, they make different predictions regarding the temporal and energy
distributions of the high-energy gamma rays. In the polar-cap model (Daugherty and Harding 1982, 1996), electrons are accelerated near the last closed field line right above the magnetic poles (see Figure 1). As the electrons curve along the strong magnetic field lines they emit curvature radiation and scatter lower energy photons via the inverse-Compton process. These photons interact with the magnetic field to produce $e^+e^-$ pairs and more photons, eventually generating a shower of particles and photons. Scattered photons with sufficient energy produce enough $e^+e^-$ pairs to short out the acceleration potential which causes a “super-exponential” cutoff in the energy spectrum between 1 and 20 GeV (Baring and Harding 2001).

Outer-gap (Cheng and Ruderman 1986; Romani 1996) models put the acceleration regions in the outer magnetosphere near the light cylinder. Charges pulled from the polar cap cannot populate the region between the null surface and light cylinder resulting in a vacuum gap which causes particle acceleration. The magnetic field is weaker in this “outer gap”, compared to near the polar cap so pair production does not limit the acceleration potential. Particle acceleration can also occur in a thin, slot gap (which follows the last closed magnetic field line) connecting the polar-cap and outer-gap acceleration regions. Like the outer-gap models, the magnetic field in these slot-gap models (Arons 1983; Muslimov and Harding 2004) does not limit the acceleration potential. Thus the outer-gap and slot-gap models can potentially produce photons of a few hundred GeV. Any detection of photons above 100 GeV would clearly favor the outer-gap and slot-gap models over the polar-cap model. Additionally, detailed measurements of the pulse profiles of gamma-rays above 10 MeV could discriminate between the various models.

Like most pulsars, PSR B1951+32 was first detected at radio wavelengths. Observations revealed an object in the CTB 80 radio synchrotron nebula with a 39.5 ms period (Kulkarni et al. 1988). Further observations and analysis demonstrated the pulsar had a characteristic
age of $1.1 \times 10^5$ yr, a surface magnetic field of $4.9 \times 10^{11}$ G and a rotational energy loss rate of $3.7 \times 10^{36}$ ergs/s. While both radio and X-ray observations show a single peak in the pulsar light curve (Kulkarni et al. 1988; Ögelman & Buccheri 1987), gamma rays detected by EGRET exhibit a double-peaked profile with neither peak matching the radio peak. No evidence for inter-peak emission is found in the EGRET data. Additionally, the EGRET data show no evidence for a cut-off in the pulsed emission up to $\sim 20$ GeV (Ramanamurthy et al. 1995).

Previous observations at TeV energies have produced only upper limits on both steady and pulsed emission from PSR B1951+32 (Srinivasan et al. 1997). Recently, the MAGIC collaboration carried out observations above 75 GeV and found no evidence for pulsed emission (Albert et al. 2007). They quote a 95% c.l. upper limit to the pulsed gamma-ray flux of $< 4.3 \times 10^{-11}$ photons/cm²/s above 75 GeV.

2. Observations with STACEE

Located at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico, STACEE detects gamma rays above $\sim 100$ GeV by sampling the Cherenkov light from air showers produced when a gamma ray interacts in the upper atmosphere. STACEE utilizes the large mirror area of a solar heliostat array to increase the sensitivity to low energy showers ($E \sim 100$ GeV) as compared to single-dish gamma-ray telescopes. Heliostats with 37 m² reflection area (25 1.2 m $\times$ 1.2 m mirrors comprise each heliostat) reflect the Cherenkov light to secondary mirrors on the receiver tower. The secondary mirrors then focus the light from each heliostat onto separate photomultiplier tubes (PMTs). STACEE uses 64 different heliostats to sample the Cherenkov shower front at 64 independent locations spread over a $\sim 2 \times 10^4$ m² area on the ground. The large mirror area allows STACEE to operate with an energy threshold around 100 GeV.
STACEE employs a two-level trigger system to identify air showers amidst the night-sky background light and to discriminate gamma rays from the far more abundant charged cosmic rays. The electronic signals from each PMT are AC-coupled, amplified and fanned-out for processing. In the trigger electronics chain, each PMT output is discriminated and digitally delayed in order to align the signals from each heliostat in a given subgroup. The delays correct for differences in light travel times from the heliostats to PMTs and in signal propagation times through the electronics. A minimum number of PMT channels are required to have fired within a given coincidence window of typically 12 ns. Normal STACEE operations use 8 subgroups, each with 8 PMT signals, and a Level-1 trigger requires 5 PMTs above threshold in a subgroup to fire. These Level-1 signals are aligned in time using additional delays. A full-detector (Level-2) trigger is generated upon exceeding a specified number of synchronous Level-1 triggers. Normal STACEE operations requires five Level-1 triggers to generate a Level-2 trigger. Upon generation of a Level-2 trigger, a GPS-timestamped event is written to disk. Sky monitoring and heliostat status data are continuously recorded throughout an observing night by an independent system. For a more complete description of the STACEE detector and its operation, see (Hanna et al. 2002; Gingrich et al. 2005).

The PMT signals are also sent to high-speed flash analog-to-digital converters (FADCs) which are read out upon receipt of a Level-2 trigger. The information gained from sampling the PMT signals at 1GS/s using the FADCs was utilized in the offline data analysis to enhance STACEE’s sensitivity to gamma rays.

STACEE’s latitude of 34.96°N coupled with PSR B1951+32’s declination of 32.88° made for favorable observations. During three periods – June-July 2005, September 2005, and June 2006 – a total of 15.1 hours of PSR B1951+32 data were taken on clear, moonless nights at an average elevation of 82.5 degrees. Usually, STACEE observes in ON/OFF
mode where the source is tracked for 28 minutes (ON run) along with a background region (OFF run) following the same path on the sky. In order to maximize the amount of data recorded from PSR B1951+32, no background (OFF) observations were taken. Background observations are unnecessary because we searched for a signal in the phase plot after folding the trigger times at the radio pulsar period.

3. Analysis

3.1. Cleaning and Gamma-ray Enhancement Analysis

STACEE observed PSR B1951+32 on 18 different nights during 2005-06. After all the data for a given night were acquired, the trigger and FADC data were merged on an event-by-event basis, and the sky monitoring and heliostat status data were integrated into the subsequent file. Various data quality selection routines were applied on the fully-merged data files. Sections of data taken with malfunctioning hardware, unstable atmospheric conditions or excessive light contamination were flagged and removed from the data analysis stream. For a detailed description of the standard selection procedure see (Bramel et al. 2005).

Because the STACEE PSR B1951+32 data were obtained using non-standard procedures, the application of data quality cuts also differed from the standard procedure. For example, the standard method to determine both the stability of sky conditions and changes in background light contamination relies on comparing the subgroup trigger rates between the ON and OFF runs. Under stable conditions, the rates and fluctuations of the subgroup triggers behave similarly for ON and OFF runs. For PSR B1951+32, no OFF runs were taken and thus a different stability check was adopted.

The Level-1 trigger rates for each run were binned in ten-second intervals and fit as
a function of time. A quadratic polynomial was fit to the trigger rate as a function of elevation. If the residual between the fit and the recorded rate in any interval was more than three times the RMS of all the residuals for that subgroup, the subgroup was flagged for that interval. Any time-interval with three flagged subgroups was declared bad and the one-minute time period centered on the bin was removed from the analysis stream. Thus data taken under unstable weather conditions or with increased light contamination were eliminated. Additionally, all data taken with more than two sustained heliostat malfunctions were eliminated, as were any data without all 64 channels of FADC information. Data quality selection cuts eliminated 2.6 hours of observations resulting in 12.5 hours of clean data to analyze for a pulsed gamma-ray signal.

Further cuts were applied to the STACEE data to discriminate between potential gamma rays and the background cosmic rays. In STACEE’s energy range, gamma-ray shower fronts assume a spherical shape because most of the light originates from a small region where the number of particles in the shower is a maximum. In contrast, the hadronic nature of cosmic-ray interactions produces more variation in the shower development so cosmic-ray shower fronts are less uniform than those for gamma rays. A procedure referred to here as the grid alignment technique (Smith et al. 2006) exploits this difference to enrich the gamma-ray signal strength. Briefly, light-travel and detector transit time differences result in the FADC samples arriving at different times in their respective buffers. The light-travel differences rely on the position of the shower core relative to the heliostat layout. For each of a grid of assumed shower core locations, the FADC buffers are time-corrected, added together and the ratio of the resulting pulse height to pulse width is calculated. The assumed core location that gives the maximum height-to-width ratio is taken to be the true shower core. As shown in Figure 2, the distribution of this ratio drops off more quickly for gamma rays than for cosmic rays as a function of distance on the ground. Comparing the maximum ratio to the ratio at a given distance from the core provides a means to reject
background cosmic rays. See Lindner et al. (2007) for a more complete description of the technique. Accounting for all data quality cuts and background rejection cuts, STACEE’s energy threshold (which is defined as the peak of STACEE’s response curve for a source with a Crab-like gamma-ray energy spectrum) is 117 GeV.

### 3.2. Timing Analysis

The arrival time of each candidate gamma-ray event recorded by STACEE is time-stamped using a GPS clock. In order to properly compare the STACEE data with a pulsar’s ephemeris, the arrival times for data passing all quality and background rejection cuts were transformed to the solar system barycenter using the JPL DE200 Planetary and Lunar Ephemeris (Standish, E.M. 1982, 1990).

To check our timing procedures we used a special setup of three PMTs to record optical data from the Crab pulsar. The location of two peaks at the proper phase after barycentering, seen in Figure 3, verifies the optical path of the STACEE detector and the proper functioning of the barycentering code.

Table 1 shows the ephemeris for PSR B1951+32 as taken from Albert et al. (2007) which was used to convert from local to solar system barycentered times. Figure 4 shows the barycenter arrival time of each candidate gamma-ray event recorded by STACEE (and which passed all cuts) folded at PSR B1951+32’s period. The shaded regions correspond to the location of the main and interpulse peak detected by EGRET (Ramanamurthy et al. 1995). No evidence for pulsed gamma-ray emission was found. Using the method of Helene (1983), a 99.9% c.l. upper limit on the number of pulsed gamma-ray events in the STACEE data was calculated.

The effective area for STACEE was determined by propagating a set of gamma-ray
shower simulations through a computer model of STACEE’s optics and electronics. The energy spectrum of the simulated gamma-ray showers matched the spectrum measured for PSR B1951+32 by EGRET (Nolan et al. 1996) and their impact parameters were distributed uniformly over STACEE’s collection area. The effective area and energy threshold were calculated by comparing the number of simulated showers to the number that triggered the computer model. The effective area was used to convert the limit on the number of gamma-ray events in the STACEE data into a limit on the pulsed gamma-ray emission from PSR B1951+32. The resulting integral flux upper limit is $< 5.26 \times 10^{-11}$ photons/cm$^2$/s above an energy threshold of 117 GeV.

### 4. Discussion

The mechanisms at work in pulsars which produce the X-ray and gamma-ray emission remain poorly understood. Consequently, any observational constraints help refine theoretical models. Based on measurements below 20 GeV by EGRET, PSR B1951+32 is one of the most promising candidates to produce gamma rays with energies detectable by current ground-based instruments. The STACEE shower-front sampling gamma-ray detector was used to observe this pulsar during 2005 and 2006. Analysis of over 15 hours of data revealed no pulsed gamma-ray emission corresponding to a integral flux upper limit of $< 5.26 \times 10^{-11}$ photons/cm$^2$/s above 117 GeV. This work represents the first constraints on PSR B1951+32 using the shower-front sampling technique and compares favorably with results from other experiments such as MAGIC.

STACEE was decommissioned in the summer of 2007, and so no further data will be taken by STACEE to improve upon this limit. However, other more sensitive gamma-ray telescopes have recently begun observations. In the northern hemisphere, VERITAS (VERITAS 2007) and MAGIC (Ferenc et al. 2005) have energy thresholds below 100 GeV.
for PSR B1951+32 (H.E.S.S.’s (Hinton 2004) location in the southern hemisphere means its energy threshold for this object is higher). NASA recently launched the GLAST (Ritz 2007) gamma-ray detector which can detect gamma rays with energies up to 300 GeV. The overlapping energy range of these instruments provides the first opportunity to measure the gamma-ray emission from PSR B9151+32 (and gamma-ray pulsars in general) with no gaps in the energy spectrum. Thus, observations over the next few years will definitively map out the emission properties of PSR B1951+32.

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Fig. 1.— Magnetospheric model of a pulsar. $\Omega$ labels the rotation axis of the neutron star and $B$ the magnetic field axis. Note the different regions of particle acceleration for the polar cap, outer gap and slot gap (Harding 2004).
Fig. 2.— Grid alignment technique (as described in the text) applied to a simulated gamma-ray shower (left) and a simulated cosmic-ray shower (right). For each specified core location on the ground, the FADC data recorded by all STACEE channels are corrected for time delays and summed. The height-to-width ratio of the resulting pulse is calculated and plotted as a function of core location. The more uniform development of gamma-ray showers compared to cosmic-ray showers gives a peaked distribution.
Fig. 3.— Phaseogram for optical data from the Crab pulsar recorded by STACEE using a special setup (Fortin 2005). The pronounced peaks at the proper phase after converting the arrival times from the local time to solar system barycenter time confirm the proper functioning of STACEE’s UTC timing and the barycentering code.
Fig. 4.— Phaseogram of candidate STACEE gamma-ray events from PSR B1951+32 folded using the radio pulsar’s ephemeris. The shaded regions correspond to the location of main pulse (0.12-0.22) and the interpulse (0.48-0.74) as seen by EGRET (Ramanamurthy et al. 1995). No evidence for a signal is seen.
Table 1: Ephemeris of PSR B1951+32 as taken from Albert et al. (2007).

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