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SEARCH FOR TeV EMISSIONS FROM PULSARS IN BINARY SYSTEMS

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ABSTRACT

A survey of binary systems containing pulsars was conducted, with the intention of detecting Galactic sources of very high energy γ-ray emission. Observations were carried out with the Whipple 10 m imaging atmospheric Cerenkov telescope. Standard analysis techniques were applied to these sources to search for steady, unpulsed emission. Periodic tests were also performed to search for emission correlated with both the orbital and spin phases, where appropriate. Analyses indicate that the binaries in this study do not emit detectable levels of very high energy photons within the sensitivity of our instrument. The flux upper limits presented here fail to seriously constrain emission models.
Subject headings: gamma rays: observations — pulsars: general

1. INTRODUCTION

Pulsar-powered binary systems (gravitationally bound systems containing at least one pulsar) represent a class of objects thought to be sources of Galactic TeV emission. In the youth of modern very high energy (VHE) astronomy, many groups reported detecting the emission of photons at those energies from binaries. These detections were usually made by observing a periodic emission of γ-rays, corresponding to the spin or orbital period of the neutron star (for a review, see Chadwick, McComb, & Turver 1990 and Weekes 1992 and references therein). More recently, as larger and more sensitive telescopes have come into use, these emissions have not been confirmed.

Of the known emitters of VHE γ-rays, four are associated with systems containing pulsars. One of these sources, the high-mass X-ray binary Centaurus X-3, is the only binary so far identified as a source of high-energy radiation, being detected at GeV (Vestrand, Sreekumar, & Mori 1997) and TeV (Chadwick et al. 1998) energies. Emission from a second binary, the Be X-ray binary PSR 1259−63, was reported by the CANGAROO collaboration, although only at the 4 σ confidence level (Kifune 1996); however, later observations failed to confirm these results. These systems were both reported as steady sources of VHE γ-ray radiation. Emission from both sources is believed to originate at a location away from the neutron star, possibly at a shock front created by the interaction of the pulsar's relativistic wind with its companion. Although the central engine powering these systems is a neutron star, there have been no confirmed detections of periodic emissions from one. These reports do not indicate that binary systems are conclusive TeV photon emitters. However, they do present evidence that these sources warrant further investigation.

The mechanisms for particle acceleration in binary systems are uncertain, but models explaining and predicting TeV emission do exist. For accretion-powered systems, these include relativistic particle beams interacting with moving gas targets (Aharonian & Atoyan 1991) and acceleration of protons via resonant absorption in the outer magnetosphere (Katz & Smith 1988). Shock acceleration models of Harding & Gaisser (1990) predict detectable levels of TeV emission from rotation-powered binary systems. In these models, the relativistic wind emanating from the pulsar produces a standing shock front where diffuse acceleration by the first-order Fermi mechanism can take place.

For this study, we observed two X-ray binaries and four millisecond radio binaries. One of the radio pulsars included in this study is a planetary system. All data were searched for the presence of unpulsed γ-ray emission. Searches for periodic emission were also conducted when applicable. We describe the collection and analysis techniques in § 2, discuss our observations and results in § 3, and finish with a brief summary and concluding statements in § 4.

2. COLLECTION AND ANALYSIS TECHNIQUES

Our ability to directly detect astrophysical γ-rays at the Earth's surface is prevented by atmospheric absorption. Fortunately at these energies, the high-energy primaries produce cascades of charged particles, or air showers.

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Galbraith & Jelley (1953) proposed that the Cerenkov radiation emitted by the charged particle components of the air showers could be used to detect VHE photons striking the atmosphere. Unlike for other energy regimes of astrophysics, which regard the atmosphere as a hindrance, it is possible to use the Earth's atmosphere as a Cerenkov detector medium so that these VHE photons can be detected. Since its inception over 30 years ago, the atmospheric Cerenkov technique remains the most sensitive technique available to effectively study photons with energies of 0.1–10.0 TeV.

The observations of pulsar-powered systems presented here were made with the 10 m imaging atmospheric Cerenkov telescope located at the Fred L. Whipple Observatory in southern Arizona. The camera consists of an array of photomultiplier tubes (PMTs) mounted at the focal plane of the reflector. The camera records images of atmospheric Cerenkov radiation initiated by high-energy photons and cosmic rays. The data in this study were collected with a 331 pixel camera, which has a field of view of approximately 5°. The telescope and its properties are discussed in more detail elsewhere (Cawley et al. 1990).

2.1. *Unpulsed Analysis*

These data were collected during the 1997/1998 and 1998/1999 observing seasons. The data acquisition system utilized a twofold coincidence prior to 1999 (see Cawley et al. 1990 for details), and a twofold pattern selection trigger (Bradbury et al. 1999) was implemented in the spring of 1999. The events passing the triggering criteria were analyzed off-line, using a moment analysis routine (Reynolds et al. 1993). Each event is parameterized with a shape (length and width), orientation (alpha), and light distribution (concentration, asymmetry, and tube brightness). Hadronic and γ-ray–induced showers have distinct differences in the angular distribution of light and the orientation of their images. Using these differences, we are able to extract γ-ray signals from a large hadronic background (see Jelley & Porter 1963 and Jelley 1967 for a more detailed discussion). Using contemporaneous data of the Crab Nebula (a standard candle in TeV astronomy), we optimize the cuts made on the above parameters to identify candidate γ-rays.

The data in this study were collected using two modes of operation: ON/OFF and TRACKING. In the ON/OFF mode, an ON run tracks the candidate source position at the center of the field of view for 28 sidereal minutes. The ON run is followed by an OFF (control) run, which tracks the same azimuth and elevation as the ON run, enabling any biases due to terrestrial or atmospheric effects to be eliminated. Differences in night-sky brightness and star fields are eliminated with software padding (Cawley 1993), in which Gaussian noise is added to equalize the noise in the PMTs.

The majority of the observations utilized for this report were made in TRACKING mode. When observing in this manner, the telescope tracks only the putative source position for 28 sidereal minutes, with no control observations being made. The standard analysis method for TRACKING observations (Catanese et al. 1998) makes use of the alpha parameter's distribution. Events with small values of alpha (0°–10°) are considered γ-ray–like, and those with large alpha angles (20°–65°) are assumed to be background and independent of γ-ray emission. A large collection of contemporaneous nonsource data is analyzed, giving the shape of the alpha distribution in the absence of a source of γ-rays. A tracking ratio is determined, which converts the number of events in the background region to the number of background events in the source region (see Fig. 1).

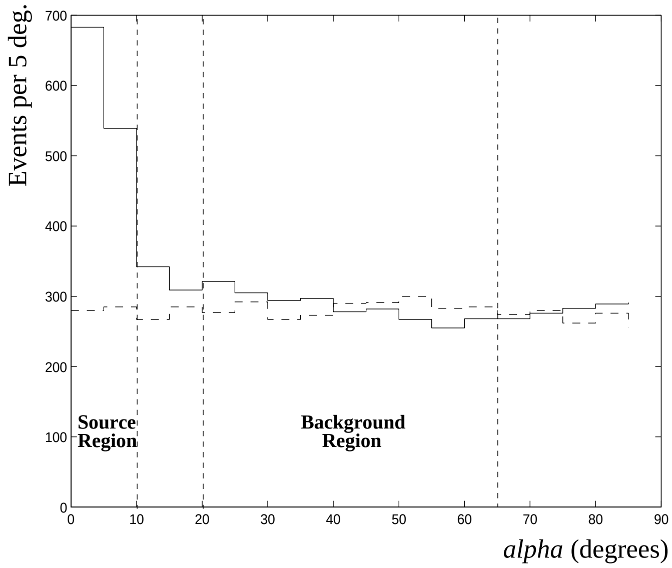

FIG. 1.—Alpha distribution of events passing shape and light distribution cuts from the direction of the Crab Nebula. The solid and dashed lines indicate ON- and OFF-run alpha distributions, respectively. The source and background regions used in the tracking analysis are indicated.

A tracking ratio (ρ) and its uncertainty ($\Delta\rho$) are given by

$$\rho \pm \Delta\rho = \frac{N_{\rm src}}{N_{\rm bkg}} \pm \frac{N_{\rm src}}{N_{\rm bkg}} \sqrt{\frac{1}{N_{\rm src}} + \frac{1}{N_{\rm bkg}}} \,, \qquad (1)$$

where $N_{\rm src}$ is the number of events in the source region and $N_{\rm bkg}$ is the number of events in the background region. The tracking ratios used for the data sets presented here were determined using the above method. The ratios were determined to be 0.2215 ± 0.0053 for the 1997/1998 data set and 0.2277 ± 0.0047 for the 1998/1999 data set. The significance of any excess was calculated using a simple propagation of errors,

$$S = \frac{N_{\rm src} - \rho N_{\rm bkg}}{\sqrt{N_{\rm src} + \rho^2 N_{\rm bkg} + \Delta\rho^2 N_{\rm bkg}^2}} \,, \qquad (2)$$

with upper limits derived using the method of Helene (1983) and determined to a confidence level of 99.9%.

2.2. *Periodic Analysis*

Before any attempt at detecting periodicity in a system is made, it is crucial to remove any contributions to the arrival times that have been introduced by the time-dependent relative motions of the source and the observatory. For accurate phase alignment to be carried out over long periods of time, the arrival times of Cerenkov events must be corrected to the solar system barycenter, considered here as an inertial reference point. The arrival times of Cerenkov events were registered by a GPS clock and an oscillator calibrated by a GPS second mark to achieve an absolute time resolution of 0.1 μs. All arrival times were then transformed to the solar system barycenter using the JPL DE200 planetary ephemerides (Standish 1982).

Just as the Earth's orbit induces timing errors, the orbit of a potential source in a binary system also produces timing errors. In order to make these corrections, we must determine the time of flight from the source position to the projected plane of the orbit. This procedure is relatively simple for binary systems with circular orbits; however, for systems whose eccentricity is not small, the procedure is more complicated, requiring precise measurements of the orbital parameters and the source location in the orbit.

The orbital parameters are determined at a time of reference (epoch of observations) and can be used to predict the orientation of the orbit and the location of the secondary in the orbit at any time. Once the exact positions are known, the time correction is taken to be the time of flight from the position of the source in its true orbit to its position in its projected orbit (for a rigorous treatment of the procedure, see Blandford & Teukolsky 1976).

After all time corrections have been applied, the events have the appearance of originating and being recorded in an inertial reference frame. These corrected event times can then be tested for the presence of signals that arise from processes that depend on the spin or orbital dynamics of the suspected source.

Calibration of the timing systems at the Whipple Observatory was accomplished with optical observations conducted in 1996 December using the 10 m reflector (Srinivasan et al. 1997). The Crab pulsar was observed with an aperture on the central phototube, allowing the telescope to operate as an optical telescope with a photometer at its focus. The phase analysis of the event arrival times yielded a clear detection of pulsed optical emission from the Crab pulsar, thereby demonstrating the validity of the timing, data acquisition, and analysis software in the presence of a pulsed signal (Srinivasan et al. 1997; Lessard et al. 2000).

The corrected event times (t) were phase (ϕ) folded modulo the frequency (ν) relevant to the epoch (t_0) and the source under study, according to

$$\phi = \phi_0 + \nu(t - t_0) + \tfrac{1}{2}\dot{\nu}(t - t_0)^2 + \tfrac{1}{6}\ddot{\nu}(t - t_0)^3 . \quad (3)$$

The χ^2 test was applied to the resulting histogram to measure the deviation of the folded data from that expected for a distribution in which there is no periodic signal. The results of any tests that rely on binned data are dependent on the binning process (i.e., the number of bins used).

In order to remove bias resulting from the binning of the data, the Z_m^2 test (Buccheri et al. 1983) was performed. This test has the disadvantage that the optimal number of harmonics (m) that should be used is dependent on the pulse shape, which is unknown. Sums of a small number of harmonics are more sensitive to broad, sinusoidal pulses, whereas sums of a large number of harmonics are most sensitive to narrow features in the light curve. Sources in this study were subjected to the χ^2, Z_2^2, and Z_{10}^2 tests.

The data sets were searched for evidence of emission modulated at the orbital period. Standard analysis techniques were independently conducted on those data near phases 0.00, 0.25, 0.50, and 0.75. The 99.9% confidence level flux upper limits from each of the orbital phases were derived using the method of Helene (1983).

3. OBSERVATIONS AND RESULTS

A set of six binaries were observed for this study. These include two X-ray sources (LS I +61°303 and 2A 1704+241) and four millisecond radio pulsars (PSR B1257+12, PSR B1534+12, PSR B1639+36B, and PSR B1957+20). The data sets for each object were tested for the presence of a steady, unpulsed γ-ray signal and periodic emission at the orbital and pulsar period, when possible. All upper limits reported here have a peak energy response at 500 GeV, except LS I +61°303, which incorporates an earlier data set with a peak energy response of 350 GeV. Upper limits are reported at the 99.9% confidence level for both steady and periodic emission.

3.1. *LS I +61°303*

LS I +61°303 is an X-ray–emitting binary system containing a 10 $M_\odot$ Be star and a compact object, most likely a neutron star (Frail & Hjellming 1991). This binary exhibits bright radio outbursts with a period of approximately 26.5 days (Taylor & Gregory 1984). It is likely that the X-ray flux results from inverse Compton scattering of stellar photons off a relativistic electron population produced at a shock resulting from the interaction of the relativistic wind of a young pulsar with the stellar wind of the Be companion (Maraschi & Treves 1981; Tavani 1995). The observed luminosity and the featureless power-law spectrum (Strickman et al. 1998) are both consistent with the shock interpretation. The luminosity of LS I +61°303 is comparable to that observed from PSR B1259−63 (Kaspi et al. 1995), for which a similar mechanism has been invoked (Tavani, Arons, & Kaspi 1994). This interpretation is supported by the lack of observed X-ray pulsations, since the X-ray emission will be produced well outside of the neutron star's magnetosphere. In this scenario, the X-ray peak should occur near periastron and the radio outburst should be shifted by approximately 50% in phase. This shift has been reported by Harrison et al. (2000), suggesting this as a plausible model.

This system is of particular interest because it is one of a very few radio-emitting X-ray binaries (Gregory & Taylor 1978; Taylor & Gregory 1982). The interest in LS I +61°303 is also reinforced by the fact that it has been identified as a likely counterpart to the *COS B* and EGRET γ-ray source 2CG 135+01 (≡ 2EG J0241+6118; Bignami & Hermsen 1983; Kniffen et al. 1997). The γ-ray source 2CG 135+01 displays slight variability (Tavani et al. 1998; McLaughlin et al. 1996), with an integral flux of 9.2×10^{-7} cm^{-2} s^{-1} and spectral index of approximately 2 for energies above 100 MeV (Kniffen et al. 1997). Extrapolating the spectrum to an energy of 500 GeV yields a flux well above our detection sensitivity.

If 2CG 135+01 is associated with the radio-loud X-ray binary LS I +61°303, various models have been put forth to explain the high-energy emission. One of these models utilizes a shock front formed by the interaction of the relativistic wind of a rapidly rotating neutron star with the gaseous material outflowing from the massive companion. Variability of high-energy emission is expected because of the changing hydrodynamic and radiative conditions of the pulsar, as well as the time variability of the mass outflow from the stellar companion (Tavani et al. 1998). The extent of the time variability and spectrum depends on the details of the models; however, an increased high-energy emission is expected at periastron, when the magnetic field at the shock is enhanced. To date, no evidence has been found for an enhancement of the high-energy emission at the orbital period of LS I +61°303.

TABLE 1
RESULTS OF THE SEARCH FOR STEADY, UNPULSED, HIGH-ENERGY EMISSION FROM LS I +61°303

Data Set	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
1994–1996	1397.5	1.39	≤ 0.92[a]
1998	424.7	1.50	≤ 1.23[b]
Combined data sets	1822.2	0.78	≤ 0.88[b]

[a] Energy threshold of 350 GeV.
[b] Energy threshold of 500 GeV.

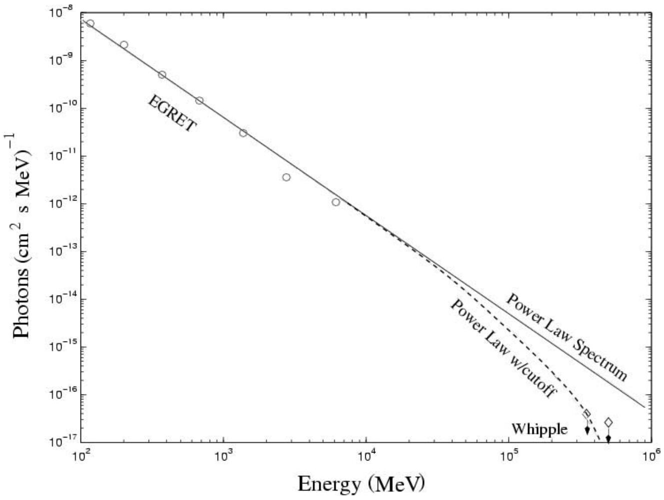

FIG. 2.—Fluxes of 2CG 135+01 seen at EGRET energies (*circles*) and the flux upper limits of LS I +61°303 reported here (*diamonds*). The solid line represents an extrapolation of the flux from EGRET energies with a spectral index of 2.05 (Kniffen et al. 1997). The dashed line represents a power-law spectrum with a high-energy cutoff at 140 GeV.

The database used in this study consists of archival observations made during the years 1994–1996, as well as observations made in 1998. A total of 25 ON/OFF pairs and 69 TRACKING runs were combined in this analysis. These data were searched for a steady, unpulsed TeV emission using the standard analysis methods described in § 2. Parameter cuts were applied to the archival data set (1994–1996) yielding an energy threshold of approximately 350 GeV. Parameter cuts were independently applied to the 1998 data set. The results of these analyses are given in Table 1. In order to maximize our time on source and to more completely sample the orbital period, the data sets were combined. This was accomplished by applying a set of size-dependent cuts, Extended Supercuts (Mohanty et al. 1998; Lessard et al. 2000), to the archival data in order to match their energy response to that of the 1998 data set. The results of the unpulsed analysis and the derived 99.9% confidence level flux upper limits are presented in Table 1. No evidence of TeV emission was seen in the combined data set or in the data from individual years.

There are no predictions of emission from the X-ray binary LS I +61°303 with which to compare our derived flux upper limits. However, our upper limit requires that LS I +61°303 convert less than 1.3×10^{32} ergs s^{-1} into VHE γ-rays. We can make extrapolations from the flux emitted by 2CG 135+01 at EGRET energies to the TeV regime. The flux upper limit above 500 GeV reported here requires an exponential high-energy cutoff of less than 200 GeV. Using the flux upper limit derived from the archival data set (350 GeV), the resulting high-energy cutoff must be less than 140 GeV (see Fig. 2).

3.2. *PSR B1257+12*

The millisecond pulsar PSR B1257+12 was discovered in 1990 February (Wolszczan 1990) with the 305 m Arecibo radio telescope. With a growing time span of pulse arrival times, it gradually became clear that the arrival times exhibited an unusual variability. Other millisecond pulsars observed with the same equipment and analyzed by the same methods did not show such effects in their timing. Analysis of the period variability led to the detection and confirmation that this pulsar is the central object of the first extrasolar planetary system to be discovered (Wolszczan & Frail 1992).

Observations of the planetary system PSR B1257+12 were made with the EGRET detector on board the *CGRO* satellite. No emission was detected in the EGRET energy regime (30 MeV–10 GeV). Based on this nondetection, a flux upper limit was determined to be 4.0×10^{-8} cm^{-2} s^{-1} above 100 MeV (Fierro et al. 1995). No pulsed flux upper limits were reported for the EGRET observations.

Even though this pulsar is characterized as a solitary millisecond pulsar, it is included in this study, since the pulsar wind can interact with the planets in the system, forming a shock front. This shock front is predicted to produce γ-rays with an integral flux of 5.5×10^{-12} cm^{-2} s^{-1} above 1 TeV (Harding & de Jager 1998).

The database used for the study of PSR B1257+12 consists of one ON/OFF and eight TRACKING observations obtained in 1998 and two ON/OFF and 46 TRACKING observations collected in 1999, all using the 331 pixel camera. These data were searched for unpulsed, steady emission using the standard analysis method. No steady emission from PSR B1257+12 is evident in either the combined or individual data sets. These results and the 99.9% confidence level flux upper limits are presented in Table 2.

3.3. *PSR B1534+12*

The millisecond pulsar PSR B1534+12 was discovered in 1990 February (Wolszczan 1991) using the 305 m Arecibo radio telescope to survey high Galactic latitudes. The narrow peak in the pulse profile allowed very accurate timing measurements to be made. These timing measurements indicated that PSR B1534+12 is in an eccentric, close orbit with another compact object of roughly the same mass.

TABLE 2
RESULTS OF THE SEARCH FOR STEADY, UNPULSED EMISSION FROM PSR B1257+12 AT ENERGIES ABOVE 500 GEV

Data Set	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
1998	179.5	0.88	≤ 1.65
1999	967.6	0.56	≤ 0.70
Combined data sets	1147.1	0.85	≤ 0.68

TABLE 3

RESULTS OF THE SEARCH FOR STEADY, UNPULSED EMISSION FROM PSR B1534+12 AT ENERGIES ABOVE 500 GEV

Data Set	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
1998	274.2	1.02	$\leq$1.37
1999	288.0	0.11	$\leq$0.97
Combined data sets	562.2	0.83	$\leq$0.87

Moreover, the small spin-down rate of the pulsar implies that it is old and has a weak magnetic field. These characteristics are typical of pulsars spun up to millisecond periods by the accretion of matter from their binary companions.

PSR B1534+12 was included as part of our survey of binary systems based on predictions made by Harding & Gaisser (1990), which indicate that this system could emit detectable levels of TeV γ-rays. These γ-rays are theorized to be created in a shock front as the pulsar wind interacts with the companion neutron star's wind and magnetosphere. Harding & de Jager (1998) predict that such an interaction will produce an integral flux of 1.4×10^{-12} cm^{-2} s^{-1} above 1 TeV.

The database used in this study consists of one ON/OFF and 10 TRACKING observations obtained in 1998 and 13 TRACKING observations collected in 1999, all with the 331 pixel camera. These data were searched for unpulsed steady emission using standard parameter cuts. No evidence of TeV emission was detected from either the individual or combined data sets. The results of the analysis and the 99.9% confidence level flux upper limits are presented in Table 3.

3.4. *PSR B1639+36B and M13*

The detection of the pulsar PSR B1639+36B was first reported in 1992 (Deich et al. 1992). This binary pulsar was discovered in the globular cluster M13 as part of a search for pulsars in globular clusters with the 305 m Arecibo radio telescope. The parameters of this binary system were obtained by observing Doppler-shifted pulse periods sampled over 2 yr.

This pulsar was included in this study to test whether a conglomeration of pulsar systems could be detected in the cores of globular clusters (Smith 1993). Considering that some of the more dense globular clusters may contain hundreds of millisecond pulsars, it is not unreasonable to speculate that their net γ-ray emission may be detectable by current atmospheric Cerenkov telescopes. Assuming that the energy source that powers TeV emission in a millisecond pulsar is the rotational energy loss of a spinning-down pulsar, it is a straightforward matter to estimate the flux from a collection of pulsars. It has been estimated (Smith 1993) that if there were N pulsars in a globular cluster, each with mass M, radius R, period P, and period derivative $\dot{P}$, then there should be an integral flux, $F_{\rm GC}$, above E_γ, given by

$$F_{\rm GC} = 1.6 \times 10^{-22} \frac{M}{M_\odot} R^2 P^{-3} \dot{P} \frac{E_\gamma}{1\ \rm TeV} \times \frac{d}{1\ \rm kpc} \alpha N\ \rm cm^{-2}\ s^{-1}, \tag{4}$$

TABLE 4

RESULTS OF THE SEARCH FOR STEADY, UNPULSED EMISSION FROM PSR B1639+36B AT ENERGIES ABOVE 500 GEV

Data Set	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
1998	244.9	0.51	$\leq$1.08

where d is the distance to the globular cluster and α is the efficiency of converting rotational energy to γ-rays.

The TeV database used in the analysis of PSR B1639+36B consisted of nine TRACKING observations obtained with the 331 pixel camera in 1998. No observations of this source were conducted during the 1999 observing season. The analysis of these data using standard analysis techniques yields no evidence of steady TeV emission from the position of PSR B1639+36B as shown in Table 4.

3.5. *2A 1704+241*

Although there is no direct evidence for this system's being a binary, Garcia et al. (1983) speculate that since the X-ray emission from this system is higher than that expected from coronal emission from a solitary M giant star, the emission must be from a compact object. Although this system is believed to be a low-mass X-ray binary (LMXB), uncertainty in the mass of the M giant does not allow this classification to be certain. Optical observations preclude the possibility that part of the optical flux of this system comes from an accretion disk, thus implying that the X-ray emission is due to a more windlike accretion. This emission is reasoned to arise from a nebula which is being formed around the M giant from the slow dense wind, typical of the red giant phase (Gaudenzi & Polcaro 1999). This nebula enables the neutron star to undergo low-level accretion, giving rise to the observed X-rays, and can be used to explain the spectral peculiarities observed from the companion.

This source was included in our survey as a sample of an LMXB. It specifically was chosen because of its proximity and the fact that it has no evidence of large-scale accretion. This characteristic is desired, since the most probable models of TeV γ-ray production favor systems undergoing little or no accretion.

The TeV database used in the analysis of 2A 1704+241 consisted of 14 TRACKING observations obtained in 1998 and an additional four TRACKING observations obtained during the 1999 observing season, all made with the 331 pixel camera. No evidence of steady emission was detected from the putative source position in either the individual or combined data sets. These results are shown in Table 5.

TABLE 5

RESULTS OF THE SEARCH FOR STEADY, UNPULSED EMISSION FROM 2A 1704+241 AT ENERGIES ABOVE 500 GEV

Data Set	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
1998	352.3	−0.72	$\leq$0.72
1999	93.2	0.54	$\leq$1.71
Combined data sets	445.5	−0.42	$\leq$0.67

3.6. *PSR B1957+20*

The eclipsing millisecond pulsar PSR B1957+20 was discovered during a general survey for millisecond pulsars at the 305 m Arecibo radio telescope (Fruchter, Stinebring, & Taylor 1988). This pulsar was found to have the smallest spin-down rate and the second smallest period of all known pulsars. For a few minutes before and for more than 20 minutes after the eclipse, the radio pulses were delayed by up to 400 μs, presumably because of propagation through an ionized gas surrounding the companion. It was further speculated that this plasma may be the result of the evaporation of the companion by the pulsar's wind (Fruchter et al. 1988).

PSR B1957+20 has been the focus of high-energy (from MeV to GeV) observations as well. The balloon-borne MPE Compton Telescope observed the region containing PSR B1957+20 (Brink et al. 1990), and the resulting data were searched for γ-ray emission correlated with the 9 hr orbital period. No detection was reported in the energy range 1–10 MeV, and an upper limit of the luminosity of less than 10^{33} ergs s^{-1} was established. The region containing the pulsar was also searched several times by the *COS B* satellite (Brink et al. 1990). A histogram analysis showed no significant effect when the arrival times were folded with the orbital period. A bin-free cluster analysis was applied to the data set. Two clusters of data points were observed near the Lagrangian point L4, having a chance occurrence of less than 10^{-3}. The corresponding flux, if the detection is assumed real, is 4.0×10^{-6} cm^{-2} s^{-1}, resulting in a luminosity of 5.8×10^{31} ergs s^{-1} in the energy range 50 MeV–5 GeV. The most recent high-energy observations have been carried out by EGRET. An unpulsed analysis resulted in a flux upper limit of 16.8×10^{-8} cm^{-2} s^{-1} (Fierro et al. 1995) for energies greater than 100 MeV. A search for emission from the L4 point in the EGRET energies (50–5000 MeV) resulted in a flux upper limit of 4.2×10^{-8} cm^{-2} s^{-1} (Buccheri et al. 1996), significantly lower than the result from the *COS B* observations.

The pulsar PSR B1957+20 has been observed by a number of groups at energies similar to those in this study. The Potchefstroom group (Brink et al. 1990) reported a marginal detection from the L4 point with a flux of 1.6×10^{-10} cm^{-2} s^{-1} above 2.7 TeV. However, a later report by the same group failed to confirm this detection. Other groups, including the Haleakala (Finley 1990), Pachmarhi (Acharya et al. 1990), and Durham (Brazier et al. 1990) collaborations, have all observed PSR B1957+20, with no significant detections of either unpulsed emission or emission correlated to the spin or orbital phases.

According to the model of Harding & Gaisser (1990), PSR B1957+20 should have the highest flux of TeV γ-rays from any millisecond pulsar in a binary system observable with our instrument. Although PSR B1957+20 has been observed by many groups, the published flux levels cannot interestingly constrain the predictions of the shock model.

TABLE 6
RESULTS OF THE SEARCH FOR STEADY, UNPULSED TEV EMISSION FROM PSR B1957+20

Data Set	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
1998	149.1	0.89	$\leq$1.13

The pulsar PSR B1957+20 was only observed during the 1998 observing season. Only six TRACKING runs were obtained during this time. The standard analysis was applied to these data and yielded no evidence of steady TeV emission from the position of PSR B1957+20. The results of this analysis, along with the 99.9% confidence level flux upper limit, are given in Table 6.

4. SUMMARY AND CONCLUSIONS

This study was conducted to determine if pulsars in binary systems produce detectable levels of VHE photons, as has been reported in the past. A subset of binary systems containing pulsars was studied as part of an ongoing program to detect sources of Galactic TeV emission. These systems included two X-ray binaries and four millisecond radio pulsars. The radio pulsar PSR B1257+12 is a planetary system. The data used in this study were collected with the 331 pixel camera during the 1997/1998 and 1998/1999 observing seasons. Table 7 summarizes the results of the search for steady, unpulsed emission from the sources included in this study. No steady emission was detected at a significant level from any system within the sensitivity of the Whipple 10 m imaging atmospheric Cerenkov telescope.

LS I +61°303 is a peculiar, high-mass X-ray source, exhibiting emission from radio to X-ray energies. This object is also positionally coincident with the high-energy γ-ray source 2CG 135+01 (Thompson et al. 1995; Lamb & Macomb 1997; Hartman et al. 1999). The low flux and the lack of pulsations at X-ray energies are consistent with emission from a shock front formed by the interaction of a pulsar's wind with the companion's stellar wind and magnetosphere. Assuming that LS I +61°303 is the high-energy source 2CG 135+01, this shock is thought to be responsible for powering the high-energy emission positionally coincident with this binary system. This shock may also produce emission at TeV energies; however, no evidence of emission was detected from the position of LS I +61°303 at flux levels within the sensitivity of our instrument. The flux upper limit reported here requires a high-energy cutoff in the EGRET spectrum to be less than 140 GeV.

Three of the systems in this study (PSR B1257+12, PSR B1534+12, and PSR B1957+20) were predicted to be sources of TeV γ-rays powered at shock fronts in the pulsar system. These shocks are suspected to accelerate protons to very high energies, at which point they interact with material in the system to produce π^0 particles that decay into

TABLE 7
SUMMARY OF THE RESULTS OF THE SEARCH FOR STEADY, UNPULSED TEV EMISSION FROM BINARY SYSTEMS CONTAINING PULSARS

Source	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
LS I +61°303	1822.2	0.78	$\leq$0.88
LS I +61°303[a]	1397.5	1.39	$\leq$0.92
PSR B1257+12	1147.1	0.85	$\leq$0.68
PSR B1534+12	562.2	0.83	$\leq$0.87
PSR B1639+36B	244.9	0.51	$\leq$1.08
2A 1704+241	445.5	−0.42	$\leq$0.67
PSR B1957+20	149.1	0.89	$\leq$1.13

NOTE.—Energy threshold over 500 GeV, except where noted.
[a] Energy threshold of 350 GeV.

TABLE 8

SUMMARY OF THE RESULTS OF THE SEARCH FOR PULSED EMISSION ABOVE 500 GeV

Source	Exposure (minutes)	χ^2/dof	Z_2^2	Z_{10}^2	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
PSR B1534+12	562.2	0.96	5.80	19.4	$\leq$1.02
PSR B1639+36B...	244.9	0.73	2.83	23.2	$\leq$1.36
PSR B1957+20	149.1	1.10	1.77	22.2	$\leq$1.36

VHE γ-rays. No evidence of emission was detected from these three objects, and the flux upper limits derived for PSR B1257+12 and PSR B1957+20 are both approximately half the predicted fluxes, requiring the combined efficiency of proton acceleration and γ-ray production to be at least a factor of 2 smaller than the modeled values. The flux upper limits for the source PSR B1534+12 were larger than the predicted flux, preventing us from constraining the model.

The pulsar PSR B1639+36B has shown no evidence of emission above 500 GeV. Although there are no predictions for emission from this pulsar, it can be used to place an upper limit of 2 on the value of αN (efficiency of converting spin-down energy to γ-rays times the number of pulsars in the globular cluster) for the globular cluster M13.

Periodic analyses were also conducted on the data, where appropriate. Those analyses included searches for emission modulated at the spin period of the pulsar and the orbital period of the binary system. PSR B1534+12, PSR B1639+36B, and PSR B1957+20 were the only sources searched for spin-modulated emission, owing to the presence of a known pulsar and the availability of accurate orbital parameters. No evidence of emission correlated to spin periods was detected from the timing analysis carried out on the subgroup of pulsars in this study. Pulsed flux upper limits were determined to a confidence level of 99.9%. The results of these analyses are provided in Table 8.

LS I +61°303, PSR B1534+12, PSR B1639+36B, and PSR B1957+20 were searched for emission modulated at the orbital periods in those systems. No evidence of orbitally modulated emission was detected within the sensitivity of our instrument. Flux upper limits were determined to a confidence level of 99.9% for each of the phase groups studied. The results of the search for signals modulated at the orbital period are summarized in Table 9.

We conclude that the binary systems in this study do not emit TeV γ-rays within the sensitivity of the Whipple 10 m imaging atmospheric Cerenkov telescope. We were unable to place strict constraints on the emission models of TeV photons from millisecond pulsars in binaries or globular clusters. In order to place more restrictive constraints on these models, instruments such as VERITAS (Weekes et al. 1997), HESS (Hermann 1997), MAGIC (Bradbury et al. 1995), STACEE (Chantell et al. 1997), and CELESTE (Giebels 1997), with greater sensitivity and the ability to operate at lower energy thresholds, are required.

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TABLE 9

SUMMARY OF THE RESULTS OF THE SEARCH FOR TeV EMISSION MODULATED AT THE ORBITAL PERIODS

Source	Phase Range (ϕ)	Exposure (minutes)	Significance (σ)	Flux Upper Limit ($\times 10^{-11}$ cm^{-2} s^{-1})
LS I +61°303	0.90– 0.10	460.5	1.32	$\leq$1.37
	0.15– 0.35	327.4	−0.18	$\leq$1.70
	0.40– 0.60	511.8	1.26	$\leq$1.79
	0.65– 0.85	138.7	1.00	$\leq$2.31
PSR B1534+12	0.90– 0.10	82.8	1.74	$\leq$2.66
	0.15– 0.35	158.5	−0.02	$\leq$1.22
	0.40–0.60	44.9	0.39	$\leq$2.87
	0.65– 0.85	190.8	−0.27	$\leq$1.11
PSR B1639+36B...	0.90– 0.10	80.2	1.27	$\leq$2.59
	0.15– 0.35	27.6	−0.72	$\leq$1.97
	0.40– 0.60	81.9	0.74	$\leq$1.81
	0.65– 0.85	55.2	−1.53	$\leq$1.13
PSR B1957+20	0.90– 0.10	27.7	0.56	$\leq$3.44
	0.15– 0.35	0.0	...	...
	0.40– 0.60	0.0	...	...
	0.65– 0.85	93.7	0.24	$\leq$0.66

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