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Observations of galactic pulsars and supernova remnants with the Whipple 10 m Imaging Atmospheric Cherenkov Telescope

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Abstract. Observations of pulsar systems and supernova remnants have been conducted at the Whipple Observatory using the 10 m imaging atmospheric Cherenkov telescope. Since the summer of 1999, a high resolution 490 pixel camera has been in place yielding a significant increase in detector sensitivity. We present the results of these observations and the implications they have on the various theories of very high energy emissions.

1 Introduction:

Pulsar systems and supernova remnants (SNRs) were observed with the Whipple 10 m imaging atmospheric Cherenkov telescope as part of an ongoing program to search for galactic sources of TeV emission. Selection of the objects included in this study was based on their similarity to detected sources and on the likelihood of emission given the various models of very high energy (VHE) photon production.

1.1 Pulsar Powered Systems

There are eight known high-energy pulsars, comprising one of the brightest classes of objects detected at EGRET energies (Hartman et al., 1999). Two of these objects, the Crab Nebula (Weekes et al., 1989) and PSR B1706-44 (Kifune et al., 1995), are confirmed emitters of VHE γ-rays. A third EGRET pulsar, Vela (Yoshikoshi et al., 1997), has been detected at TeV energies, but has yet to be independently verified. All three represent a class of objects known as plerions. Plerions have relativistic particle winds accelerated by the pulsar, which are confined by the slowly expanding remnant. Models of emission from this class of objects predict both steady, unpulsed emission and periodic emission. Unpulsed emission is thought to occur by inverse Compton scattering of ambient photons and synchrotron self-Compton scattering by the relativistic particle wind (Hillas et al., 1998; de Jager & Harding, 1992). Pulsed emission is predicted by both the outer gap (Cheng, Ho, & Ruderman, 1986) and polar cap (Daugherty & Harding, 1982) models.

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A fourth pulsar system, the high-mass X-ray binary Centaurus X-3, has been claimed to be an emitter of VHE γ-rays, and is the only binary so far identified as a source of TeV γ-rays (Chadwick et al., 1998). The mechanisms for particle acceleration in binary systems are uncertain, but models explaining and predicting TeV emission exist. For accreting binary 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). This study includes only rotation-powered binary systems. Shock acceleration models of Harding & Gaisser (1990) predict detectable levels of TeV emission from such 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.

At TeV energies, all four systems were found to be steady sources of VHE γ-ray radiation. Although the central engine powering these systems is a neutron star, there have been no confirmed detections of periodic emissions from these systems.

1.2 Shell-type Supernova Remnants

Shell-type SNRs remain a leading candidate for the acceleration sites of cosmic rays below $\sim 10^{15}$ eV. This is largely due to the success of the diffusive shock acceleration model and the realization that SNRs can satisfy the very large cosmic ray energy budget. Nevertheless, direct and conclusive evidence of particle acceleration in shell-type SNRs has been elusive.

Recent observations have revealed hard synchrotron X-ray spectra in several SNRs, suggesting the presence of nonthermally accelerated electrons at energies as high as ~ 100 TeV. Therefore, there is an expectation of a TeV γ-ray flux due to inverse Compton up-scattering of low-energy, ambient photons.

Assuming diffusive shock acceleration occurs in these objects, the population of energetic electrons implies the presence of accelerated hadrons. These particles will generate a TeV γ-ray flux as the nuclei interact with the ambient matter to produce π^0 secondaries. The observation of a hadronically-produced γ-ray flux from a SNR would represent a 'smoking gun' for the SNR theory of cosmic ray origins.

1.2.1 Cassiopeia A

Cassiopeia A (Cas A) is the shell-type remnant of a circa 1680 Galactic supernova. It would seem to be an attractive candidate for γ-ray emission; Cas A is the brightest radio source in the sky, and is relatively nearby, with a distance from Earth estimated at 3.4 kpc (Reed et al., 1995). Furthermore, Cas A is thought to be just entering its Sedov phase (Gotthelf et al., 2001), when the flux of γ-rays is expected to peak (Drury, Aharonian, & Völk, 1994).

RXTE observations of Cas A indicate the presence of accelerated electrons up to at least 40 TeV, suggesting an inverse-Compton γ-ray flux (Allen et al., 1997). Additionally, the high ambient matter density from the Wolf-Rayet progenitor's relic solar wind favors a strong hadronically-generated γ-ray flux.

At TeV energies, upper limits have been given by the Whipple group (Lessard et al., 1999) and the CAT group (Goret et al., 1999). However, the HEGRA collaboration has recently reported a detection after 232 hours of observations on Cas A (Aharonian et al., 2001). The flux they report, at 3.3% of the Crab Nebula flux above 1 TeV (5.8×10^{-13} γ cm^{-2} s^{-1}), is the smallest γ-ray flux yet observed from a TeV γ-ray source. Here we report on recent observations of Cas A using the Whipple 10 m telescope.

2 Observations and Analysis:

Observations of the pulsar and SNR systems presented here were made with the 10 m imaging atmospheric Cherenkov telescope at the Whipple Observatory located on Mt. Hopkins in southern Arizona (Cawley et al., 1990). All data were collected between Fall 1999 and Spring 2001. During this time, the telescope utilized a camera consisting of an array of 490 photomultiplier tubes mounted at the focal plane of the reflector. The instrument and its characteristics are described by Finley et al. (2001) at this conference.

2.1 Unpulsed Analysis

The observations reported here were collected in two different modes of operation, known as ON/OFF and TRACKING. In ON/OFF mode, the candidate source position is observed for 28 minutes (ON run) followed by a 28 minute reference observation (OFF run) taken at the same azimuth and elevation as the ON run. The OFF region is used to estimate the background counts in the ON region. TRACKING data are collected by observing the putative source position, with the background estimated from events whose arrival direction is not consistent with the source position (Catanese et al., 1998). Images of extensive air showers initiated by high-energy photons and cosmic rays are made by recording the Cherenkov radiation emitted as the shower propagates through the atmosphere. By making use of distinctive differences in the angular distribution of light and the orientation of the shower images, it is possible to differentiate a γ-ray initiated event from a very large hadronic background.

2.1.1 Pulsars

Included in this study are 11 known radio pulsars. All pulsar systems were treated as point sources, and subjected to standard SuperCuts analysis techniques (see Reynolds et al. (1993) and references therein for a detailed description of this method). No significant excesses of unpulsed, steady emission were detected from any of these objects, hence upper limits were calculated using the method of Helene (1983). Table 1 shows the results of the search for unpulsed emission performed on the pulsar data.

Table 1. Results of the search for steady, unpulsed emission from radio pulsars with the 490 pixel camera.

Source	Exposure (minutes)	Flux Upper Limit[a] F(E > E_p)	E_p[b] (TeV)
PSR B0114+58	445.0	< 1.06	0.52
PSR B0355+54	518.4	< 0.71	0.52
PSR J0538+2817	667.2	< 0.44	0.52
PSR B0656+14	722.4	< 0.70	0.52
PSR B0743+54	277.9	< 1.17	0.52
PSR B0820+02	305.1	< 1.50	0.43
PSR B1257+12	1052.9	< 1.47	0.43
PSR B1534+12	248.8	< 1.43	0.43
PSR B1823-13	961.6	< 0.91	1.00
PSR B1951+32	194.4	< 1.47	0.52
PSR B1957+20	166.3	< 2.91	0.43

[a] Integral flux upper limits are given at the 99.9% confidence level in units of 10^{-11}cm^{-2}s^{-1}
[b] Peak response energy of the instrument

2.1.2 Supernova Remnants

Table 2 shows the results of the search for steady emission performed on the SNR data. The systems presented include two plerions (3C58 and G21.5-0.9) and four shell-type supernova remnants (remaining objects). No significant excess emission was detected from any of these objects, hence upper limits were calculated using the method of Helene (1983).

Cas A was observed with the Whipple 10 m telescope between September of 1999 and January of 2000. For the present analysis, 36 TRACKING runs are used, comprising 16 hours of on-source data. Cas A subtends only ~ 5 arcmin at the camera, and thus has been treated as a point source for

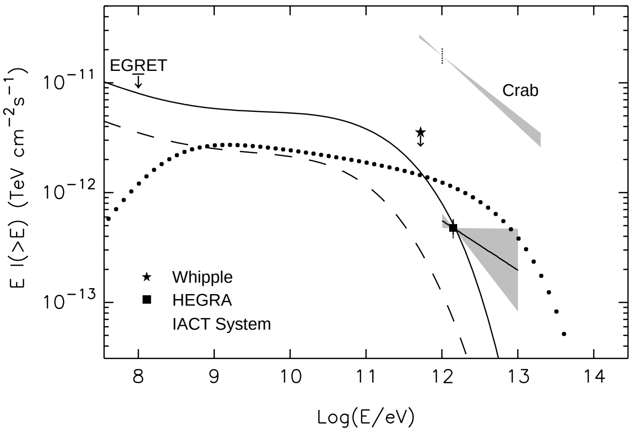

Fig. 1. Flux versus energy plot for Cas A. The Whipple flux upper limit is plotted with the EGRET upper limit, and the HEGRA detection point. The dotted line shows the predicted γ-ray flux from π^0 decay using the model of Aharonian et al. (2001). The solid and dashed lines represent the simulated bremsstrahlung and inverse Compton flux for different parameters from the model in Atoyan et al. (2000). Adapted from Aharonian et al. (2001).

this analysis. Therefore, standard analysis techniques and cuts (i.e., SuperCuts 2000) have been employed.

We have analyzed the data assuming a differential energy spectrum with index -2.5, as reported by HEGRA (Aharonian et al., 2001). No significant emission was detected, therefore we set a 99.9% confidence upper limit for emission above 520 GeV of

$$J(E > 520\ \mathrm{GeV}) < 6.8 \times 10^{-12} \quad \gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}.$$

Figure 1 shows the Whipple upper limit plotted against the model spectra from Atoyan et al. (2000). The EGRET upper limit and HEGRA flux measurement are also indicated. While the current result does not yet constrain these models, additional data may help restrict model parameters and possibly differentiate between hadronic and leptonic emission from Cas A.

Table 2. Results of the search for steady, unpulsed emission from plerionic and shell-type supernova remnants with the 490 pixel camera.

Source	Exposure (minutes)	Flux Upper Limit[a] F(E > E_p)	E_p[b] (TeV)
3C58	245.7	<1.31	0.50
G21.5-0.9	138.7	<2.90	1.25
CTA 1	320.5	<1.25	0.62
G156.2+5.7	221.8	<0.99	0.43
SN386	300.2	<0.20	3.30
Cas A	974.8	<0.68	0.52

[a]Integral flux upper limits are given at the 99.9% confidence level in units of 10^{-11}cm^{-2}s^{-1}
[b]Peak response energy of the instrument

2.2 Periodic Analysis

Calibration of the timing systems at the Whipple Observatory was accomplished with optical observations conducted in December 1996 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.

The arrival times of Cherenkov events were recorded by a GPS clock and a 10 MHz oscillator calibrated by a GPS second mark to achieve an absolute time resolution of a few μs. All arrival times were then transformed to the solar system barycenter using the JPL DE200 planetary ephemerides (Standish, 1982). The phase of each event was calculated using an ephemeris relevant to the source and epoch under study. To test for the presence of a periodic signal, χ^2 and Z_m^2 tests were performed. In order to calculate an upper limit for pulsed emission, one of two methods was employed. The first method assumes similar phase alignment with emission at EGRET energies. Upper limits were calculated using the method of Helene (1983). However, only PSR B1951+32 (Ramanamurthy et al., 1995) and PSR B0656+14 (Ramanamurthy et al., 1996) are detected at EGRET energies. Since no detections at high energies have been made of any of the remaining pulsars, a second method utilizing the Z_2^2 statistic, which assumes a sinusoidal pulse profile, was used to calculate the flux upper limit of pulsed photons. Table 3 shows the results of the periodic analysis performed on the pulsar data.

Table 3. Search for pulsed emission from isolated pulsars with the 490 pixel camera.

Source	Period (ms)	Exposure (minutes)	Flux Upper Limit[a] F(E > E_p)
PSR B0114+58	101.4	445.0	< 1.28
PSR B0355+54	156.4	518.4	< 1.02
PSR J0538+2817	143.2	667.2	< 0.95
PSR B0656+14	384.9	722.4	< 0.38
PSR B1823-13	101.5	961.6	< 1.22
PSR B1951+32	39.5	445.0	< 0.49

[a]Integral flux upper limits are given at the 99.9% confidence level in units of 10^{-11}cm^{-2}s^{-1}

3 Discussion

The data tabulated above summarize the upper limits for unpulsed and pulsed emission from the systems under study. No emission, either pulsed or unpulsed, has been detected at a significant level from the pulsar or SNR systems observed in this program.

Upper limits obtained from our analysis of the radio binary systems PSR B1257+12 and PSR B1534+12 are not sufficient to constrain the predictions made by Harding & de Jager (1998) (see Table 1).

For suitable parameter domains of the isolated pulsars, the pulsed flux upper limits presented here cannot constrain either the polar cap model or the outer gap model. The upper limit of PSR B1951+32 does, however, limit the emission region of any TeV photons to be far out in the magnetosphere (Zhang & Cheng, 1997).

As the sensitivity of single-dish Cherenkov telescopes improves and with the construction of new arrays of ground-based Cherenkov telescopes, further observations of pulsar and SNR systems should yield definitive data to address production mechanisms in these systems.

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