Search for TeV Emission from Pulsars with the Whipple Atmospheric Cherenkov Telescope

T.A. Hall[1], I.H. Bond[2], S.M. Bradbury[2], J.H. Buckley[3], A.M. Burdett[2,4], D.A. Carter-Lewis[5],
M. Catanese[5], M.F. Cawley[6], M. D'Vali[2], S.J. Fegan[4], J.P. Finley[1], J.A. Gaidos[1], G.H. Gillanders[8],
A.M. Hillas[2], J. Knapp[2], F. Krennrich[5], M.J. Lang[8], S. Le Bohec[5], R.W. Lessard[1], C. Masterson[7],
P. Moriarty[9], J. Quinn[7], H.J. Rose[2], F.W. Samuelson[5], G.H. Sembroski[1], R. Srinivasan[1],
V.V. Vassiliev[4], T.C. Weekes[4]

[1]*Department of Physics, Purdue University, West Lafayette, IN 47907, USA*
[2]*Department of Physics, Leeds University, Leeds, LS2 9JT, UK*
[3]*Department of Physics, Washington University, St. Louis, MO 63130, USA*
[4]*Fred Lawrence Whipple Observatory, Harvard-Smithsonian CfA, P.O. Box 97, Amado, AZ 85645-0097, USA*
[5]*Department of Physics and Astronomy, Iowa State University, Ames, IA 50011-3160, USA*
[6]*Physics Department, St. Patrick's College, Maynooth, County Kildare, Ireland*
[7]*Experimental Physics Department, University College, Belfield, Dublin 4, Ireland*
[8]*Department of Physics, National University of Ireland, Galway, Ireland*
[9]*Department of Physical Sciences, Galway-Mayo IT, Galway, Ireland*

Abstract

In systems containing pulsars, one may expect sufficient particle acceleration to produce extremely energetic photons. Reports of very high energy emission from such systems (Crab Nebula, PSR B1706-44, Vela, Centaurus X-3) have sparked recent interest. We present results from a search for very high energy photons (E > 350 GeV) emitted from isolated pulsars and pulsars in binary systems utilizing the Whipple 10 m atmospheric Cherenkov telescope. Our results are compared with predictions of high energy emission from pulsar systems.

1 Introduction:

Four of the eight sources of very high energy (VHE, E > 250 GeV) γ-ray radiation detected using Cherenkov imaging telescopes are associated with systems containing pulsars. In all four cases, the detections were made by observing steady, unpulsed emission of TeV γ-rays. Three of these sources (Crab Nebula (Weekes *et al.* 1989), the Vela pulsar (Yoshikoshi *et al.* 1997) and PSR B1706-44 (Kifune *et al.* 1995)) contain young, isolated, spin-powered pulsars. The fourth source, the high mass X-ray binary Centaurus X-3, is the only binary so far identified as a source of TeV γ-rays (Chadwick *et al.* 1998). Emission from a second binary system, the Be X-ray binary PSR B1259-63, has been reported by the CANGAROO collaboration, though only at a 4σ level (Kifune *et al.* 1996).

For the current study, a small subset of pulsar systems was observed as part of an ongoing program to search for galactic sources of TeV emission. These sources were chosen based on their similarity to detected sources and on the likelihood of emission given the various models of VHE photon production. These models include unpulsed emission due to inverse Compton scattering, synchrotron self-Compton scattering (Hillas *et al.* 1998 and de Jager and Harding 1992), and shock acceleration (Harding and Gaisser 1990), as well as pulsed emission as predicted by the outer gap (Cheng, Ho, and Ruderman 1986) and polar cap (Daugherty and Harding 1982) models.

Although the central engine powering these systems is a neutron star, no evidence has been found for pulsed emission from these sources at very high energies. These non-detections place limits on photon densities, magnetic field strengths, and emission regions in plerionic pulsar systems. These studies can also provide information on shock acceleration and the efficiencies for γ-ray production at the shock fronts in binary systems. The continued study of VHE γ-ray emission from isolated pulsars and pulsars in binary systems is necessary to improve our understanding of these systems.

2 Analysis and Results:

The observations of the pulsar systems presented here were made with the 10 m optical reflector of the Whipple collaboration (Cawley *et al.* 1990) located on Mt. Hopkins in southern Arizona. The camera, which consists of an array of photomultiplier tubes mounted at the focal plane of the reflector, is used to record images of atmospheric Cherenkov radiation initiated by high energy photons and cosmic rays. By making use of distinct differences in the angular distribution of light and the orientation of γ-ray and hadron shower images, we are able to extract a γ-ray signal from a large background of hadronic events.

2.1 Unpulsed Analysis:

The observations reported here were made by tracking the putative source position only, and background was estimated from observations of non-source regions and events whose direction is not consistent with the source position. The data taken on the isolated pulsars span several years of observations and two camera configurations (109 pixels with a 3.25° field of view and 151 pixels with a 3.5° field of view), whereas data collected for the binary systems were obtained with the current 331 pixel camera (4.8° field of view). No significant excesses were detected of unpulsed, steady emission from any of these objects, and upper limits were derived using the method of Helene (1983). Table 1 shows the results of the search for unpulsed emission performed on the isolated radio pulsar data. Table 2 shows the results of the search for unpulsed emission performed on the binary data taken with the 331 pixel camera.

Table 1: Results of the search for steady, unpulsed emission from isolated pulsars with the 109 and 151 pixel cameras (E > 350 GeV)

Source	Exposure (minutes)	Flux Upper Limit[a] F(E > 350 GeV)
PSR B0114+58	554.0	<0.55
PSR B0355+54	687.6	<0.70
PSR J0538+2817	533.7	<1.33
PSR B0656+14	789.1	<1.26
PSR B1823-13	589.6	<0.62
PSR B1951+32	903.4	<0.64
PSR B2334+61	109.9	<1.20

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

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 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 and folded modulo the period relevant to the epoch and the source under study.

No evidence of emission was seen from the isolated pulsars at any phase in their phase plots. Assuming similar phase emission as that reported at EGRET energies, upper limits were derived for PSR B1951+32 (Ramanamurthy *et al.* 1995) and PSR B0656+14 (Ramanamurthy *et al.* 1996) using the method of Helene (1983). Since no detections at high energies have been made of either PSR J0538+2817 or PSR B1823-13,

Table 2: Results of the search for steady, unpulsed emission from binary systems with the 331 pixel camera (E > 500 GeV)

Source	Type[a]	Predicted Flux[b] F(E >1 TeV)	Exposure (minutes)	Flux Upper Limit[c] F(E > 500 GeV)	Flux Upper Limit[c,d] F(E > 1 TeV)
LSI+61°303	HMXB	-	558.9	<1.13	<0.40
PSR J1012+5307	MRB	0.5	780	<1.13	<0.40
PSR B1257+12	MRB	0.55	407.4	<1.26	<0.45
PSR B1534+12	MRB	0.14	415.7	<1.14	<0.40
PSR B1639+64	MRB	-	244.5	<1.31	<0.46
PSR B1704+24	LMXB	-	324.4	<0.85	<0.30
PSR B1957+20	MRB	1.3	140.8	<1.55	<0.55

[a]High Mass X-ray Binary (HMXB), Millisecond Radio Binary (MRB), Low Mass X-ray Binary (LMXB)

[b]Predictions are from Harding and de Jager (1997) and Harding (1999) given in units of $10^{-11}\text{cm}^{-2}\text{s}^{-1}$.

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

[d]Integral flux upper limits obtained by extrapolating from 500 GeV with a spectral index of -2.5

upper limits are derived assuming a sinusoidal pulse profile. Table 3 shows the results of the periodic analysis performed on the isolated radio pulsar data. Results of the periodic analysis performed on binary systems, both spin and orbital searches, will be presented at this conference.

Table 3: Search for pulsed emission from isolated pulsars with the 109 and 151 cameras (E > 350 GeV)

Source	Period (milliseconds)	Exposure (minutes)	Flux Upper Limit[a] F(E > 350 GeV)
PSR J0538+2817	143.2	533.7	<1.48
PSR B0656+14	384.8	789.1	<0.46
PSR B1823-13	101.5	589.6	<0.81
PSR B1951+32	39.5	903.4	<0.20

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

3   Discussion:

The data tabulated above summarize the upper limits for unpulsed and pulsed emission from the systems under study. No emission has been detected at a significant level within the sensitivity of the telescope from the pulsar systems observed in our program. For suitable parameter domains of the isolated pulsars, the flux 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 and Cheng 1997, Srinivasan 1998). Upper limits obtained from our analysis of binary systems are not yet sufficient to constrain most of the predictions made by Harding and de Jager (1998) (see Table 2). However, the flux limit for the binary pulsar PSR B1957+20 is lower than the predicted value of Harding and de Jager (1998) by a factor of approximately two. This discrepancy can perhaps be accounted for by lower efficiency values for proton acceleration and γ-ray production.

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

4   Acknowledgements:

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