Preprint

MeV to TeV GAMMA-RAY OBSERVATIONS OF PSR 1957+20

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Abstract

We have analysed the data from the Potchefstroom air Cerenkov telescope, the COS-B satellite and the MPE Compton telescope searching for the presence of a gamma-ray signal from the direction of the eclipsing binary pulsar PSR 1957+20. Indications for possible excess emission were found at the predicted phase of the fourth Lagrange point (L_4) in both the Potchefstroom data (99.98% significance) and the COS-B data (99.9% significance). The upper limit set to the 1 to 10 MeV gamma-ray luminosity by the Compton telescope as well as an upper limit in the TeV range do not constrain existing theoretical models as applied to our results. The most reasonable origin for 50 MeV to 3 TeV radiation from L_4 appears to be due to π^0 decay from proton collisions in "Trojan matter" following the acceleration of protons in a shock front close to L_4. The ratio of the ~190 MeV to ~1 TeV gamma-ray flux implies a proton spectral index of $\simeq 2$.

I. Introduction

The 1.6 ms eclipsing pulsar, PSR 1957+20, was discovered at the Arecibo Observatory (Fruchter **et al.** 1988; Fruchter **et al.** 1990). The optical identification of the companion, which is an $\sim 0.022 M_\odot$ degenerate white dwarf, with a luminosity of $\sim 2 \times 10^{33}$ erg s^{-1} (van Paradijs **et al.** 1988; Callanan, Charles and van Paradijs 1989) supports the idea that a wind originating from the pulsar is responsible for the heating of the companion. A shock may be formed between the pulsar wind and the ablated wind from the companion where $e^\pm$ pairs with energy >1 TeV will be able to cool by synchrotron emission and inverse Compton scattering. The result may be ~1 MeV gamma-ray flux of $\sim 1.4 \times 10^{-5} \eta_\gamma$ photons cm^{-2} s^{-1} (Phinney **et al.** 1988) where η_γ is the fraction of the power in the pulsar wind converted to ~1 MeV gamma radiation. Harding (1990) predicted an associated >100 MeV flux of 5.1×10^{-7} photons cm^{-2} s^{-1} and a corresponding TeV gamma-ray flux of 5.1×10^{-11} photons cm^{-2} s^{-1} due to proton acceleration in the shock, assuming a distance of 0.5 kpc to the source (Callanan, Charles and van Paradijs 1989).

Shapiro and Teukolsky (1988) pointed out that the mass of the companion is sufficiently low for the Lagrange points L_4 and L_5 to be points of stable equilibrium. This may imply the presence of small agglomerations of target matter (probably in a plasma state due to the ionising effect of X-rays in the pulsar wind) orbiting the pulsar in the same way as the Trojan asteroids around Jupiter. If q is the white dwarf-neutron star mass ratio, then the orbital phases of L_4 and L_5 are at $0.25 \pm \theta/2\pi$ where $\theta = \tan^{-1}[\sqrt{3}(1+q)/(1-q)]$. These values correspond to phase positions 0.083 and 0.417 respectively. Their orbital extent (duty cycle) is however unknown. Since we are dealing with a search for gamma-rays, the Lagrange points are of great importance because if there exists some matter it may serve as target material for incident relativistic particles resulting in the production of gamma-rays. We therefore decided to look for a DC excess in the orbit around L_4 and L_5. Such a detection could also reveal some information about the nature of the matter. Our preliminary reports on observations done in 1988 (von Ballmoos **et al.** 1989; Raubenheimer **et al.** 1990) indicated possible emission of gamma-rays from L_4. We have continued to make TeV gamma-ray observations of PSR 1957+20 in 1989, obtaining a final data base double the size of the original and a complete orbital coverage. A more thorough investigation revealed further details concerning L_4. In section II we show that both the COS-B and Potchefstroom data indicate the possibility of gamma-ray emission from L_4, but that the Compton data is not sensitive enough to verify this effect. In section III we discuss the implications of these results.

Due to the long time intervals between the discovery of PSR 1957+20 in the radio band and both the Compton telescope flight and the COS-B satellite observations (7 to 13 years), precise pulsar parameters valid for the epochs of these gamma-ray experiments were not available and therefore the analysis of the data searching for pulsed emission at 1.6 ms has not been done. Results on the latter for the Potchefstroom data will be reported elsewhere.

II. Results

We have used the Solar System Barycentre corrected arrival times of the photons coming from the direction of the pulsar as detected by three different gamma-ray experiments: (1) the air Cerenkov telescope of the Potchefstroom University (De Jager **et al.** 1986) which observed PSR 1957+20 above 2.7 TeV during 1988 and 1989; (2) the COS-B satellite, operating from August 1975 up to April 1982 (50 to 5000 MeV, Scarsi **et al.** 1977) and (3) the balloon borne Compton telescope, flown on May 14, 1979 (1 to 10 MeV, Schönfelder **et al.** 1982).

a) Potchefstroom air Cerenkov telescope

Two series of observations of the eclipsing pulsar were made at large zenith angles ($47.7^\circ \leq z \leq 60.6^\circ$) using the Nooitgedacht air Cerenkov telescope of the Potchefstroom University which operated at a threshold energy of $\simeq$2.7 TeV for this object (see Nel **et al.** 1990 for the calculation of the threshold energy) between 6 and 11 September 1988 and again from 12 June to 1 September 1989. The relevant data for each observation are given in Table 1. Observation 9 was excluded from analysis because of poor counting statistics due to intermittent cloud coverage. We therefore have 14293 counts in the total observation time of 27.6 hours, covering all orbital phases of PSR 1957+20 at least twice.

Since no simultaneous OFF-source measurements were possible, we had to estimate the background count rate, λ, by fitting the function $\lambda = \lambda_o \cos^b z$ through the data for each observation, where z is the zenith angle and λ_o is the count rate at z = 0. This law appears to be valid for most air Cerenkov experiments (see Cawley **et al.** 1990; De Jager **et al.** 1986 and Acharaya **et al.** 1990). If a signal is present, the fit thus obtained will represent an average for both signal and background, but the quality of the fit, as well as the credibility of the identification of the signal, increases with decreasing emission time. In applying the above procedure we have split each observation into 10-minute intervals to obtain satisfactorily statistics. The statistic $\sigma_i = N_i/\sqrt{N_b}$ which is expected to be standard Gaussian distributed in the absence of a signal was then calculated for each 10-minute interval, Δt, where N_i is the number of counts in the i-th interval and $N_b = \lambda_i \times \Delta t$ gives an estimate of the expected background events within the same interval. The distribution of σ_i is compared against the standard Gaussian distribution in Figure 1. The mean of the distribution is

0.09 ± 0.08 and the standard deviation is 0.98, which leads to the conclusion that the data is well acceptable for analysis. On the positive side of the distribution we see larger excesses which correspond to the expected phase positions for TeV gamma ray emission.

Table 1: Potchefstroom air Cerenkov telescope* and

COS-B satellite# observations

Starting Time	Number of Events	Orbital Phase Interval
*7411.2222[a]	2215	0.96 - 0.42
7413.2222	1966	0.20 - 0.58
7414.2569	1851	0.91 - 0.14
7416.2569	1431	0.14 - 0.45
7690.4757	1470	0.11 - 0.49
7691.5208	1007	0.80 - 0.06
7707.5903	2660	0.47 - 0.86
7767.2326	1693	0.01 - 0.52
7770.2187	855	0.83 - 0.36
# 2744[a]	149	16.73[b]
2892	176	19.70[b]
3448	288	19.58[b]
4914	118	53.98[b]

a) JD-2440000; b) effective time (days)

The orbital period can be exactly divided into 55 phase bins of 10 minutes each, giving a bin width equal to the original integration time for each value of σ_i. Each σ_i was assigned to its appropriate phase bin and the combined significance was calculated for each phase bin (see Figure 2a). Considering emission from the Lagrange points, the L_4 orbital phase position, 0.083; shows a positive excess with a combined significance of 3.7σ or 99.99%. The significance decreases to 99.98% when the negative search at L_5 is included. The average signal above background, calculated over 10 minutes for the three observations of L_4, is $(17 \pm 9)\%$. The large error reflects mainly the variability of the signal. The corresponding flux for an $E^{-2.6}$ differential spectrum is $\Phi_T(>2.7\mathrm{TeV}) = 1.6 \times 10^{-10}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

It is important to mention that all three observations covering L_4 give a positive contribution to the combined significance of 3.7σ. Figure 3 illustrates the strongest effect and it is clear that a conservative estimate of the beamwidth is $\simeq$14 minutes. This corresponds to an effective gamma radiation interval which subtends a solid angle of $\Delta\Omega \simeq 0.02$ sr, giving a TeV gamma-ray luminosity of $L_\gamma(>2.7TeV) = 3.3 \times 10^{31}(d/0.5\mathrm{kpc})^2(\Delta\Omega/0.02\mathrm{sr})$ erg s^{-1}. The spin-down power of the pulsar which may be intercepted by the matter is

$$L_I = f \times \dot{E}\Delta\Omega/4\pi = f \times 6.9 \times 10^{32}\left(\frac{\Delta\Omega}{0.02\mathrm{sr}}\right)\ \mathrm{erg\ s^{-1}} \qquad (1)$$

where we assumed the moment of inertia $I = 3 \times 10^{45}$ g cm^2 for a neutron star with radius $R = 1.6 \times 10^6$ cm to calculate the spin-down energy loss rate $\dot{E}$. The factor f is an anisotropy factor for the pulsar wind which may be different from 1 due, for example, to the $\sin^2\theta$ dependency of the pulsar magnetic dipole radiation. The observed TeV gamma-ray conversion efficiency is therefore $\eta_\gamma = (L_\gamma/L_1) = 0.05f^{-1}$.

b) COS-B satellite Data

The region of the galactic plane containing PSR 1957+20 was observed by the COS-B satellite several times during the lifetime of the satellite. Table 1 shows the parameters of the COS-B observations used for this analysis. The second column gives the total number of photons collected for each observation in an acceptance cone centred on the pulsar and optimizing the signal-to-noise ratio (Buccheri **et al.** 1983). The error on the orbital period is negligible when the orbital parameters of Fruchter **et al.** (1990) are extrapolated back to the epochs of the COS-B satellite observations. A histogram analysis (Figure 2b) of all the 731 selected arrival times, folded with the orbital period (using 25 bins in order to have sufficient statistics per bin), does not show any significant effect.

To investigate the presence of small scale structures in the gamma-ray emission along the orbit, a bin-free cluster analysis (Buccheri **et al.** 1988) was applied to the arrival times of the 731 collected photons. Figure 2c shows the phase density derived accordingly; two very short clusters are seen in the phase intervals (0.080 - 0.082) and (0.092 - 0.095), i.e. very near to and on both sides of the phase position of the Lagrange point L_4. The probability for this COS-B detection at L_4, and taking the negative result at L_5 into account, is less than 10^{-3} for chance occurrence from poissonian distributed times. It is clear from Figure 3 that the orbital position of the two clusters coincide well with the detected TeV gamma-ray profile. The clusters consist of 7 and 10 photons respectively. The cluster analysis is biased towards the detection of narrow clusters so that the time interval of radiation may be underestimated. If we assume that the same physical process is responsible for both the ~190 MeV and TeV gamma radiation, we may assume a similar effective time interval of ≃14 minutes. The corresponding flux above 50 MeV in a 14-minute orbital interval is 4.0×10^{-6} photons cm^{-2} s^{-1} which results in a gamma-ray luminosity of $L_\gamma(50\text{MeV} < E_\gamma < 5\text{GeV}) = 5.8 \times 10^{31}$ erg s^{-1}. From this result and equation (1) it is clear that the gamma-ray conversion efficiency is the same as in the TeV band. The total flux from the two clusters, averaged over the whole orbit is 1.2×10^{-7} photons cm^{-2} s^{-1}, well below the sensitivity limit of detection of a point source by COS-B.

c) Compton telescope Data

The region of the sky containing PSR 1957+20 was observed during the last few hours of a balloon flight of the MPE Compton telescope on May 14, 1979. Orbital phases 0.38 to 0.74 were not observed. All gamma-rays with event-circles (see Schönfelder **et al.** 1984) passing through a bin of 4.5° radius around PSR 1957+20 were accepted; the corresponding background count rate was determined at the position of the mirror point (von Ballmoos, Diehl and

Schönfelder 1987). The results are shown in Figure 2d which shows the background subtracted count rate per 40 minutes as a function of orbital phase.

No significant positive signal can be seen in the Figure 2d; the data are everywhere compatible with zero signal. Even for smaller phase intervals (10 minutes) no excess was found at the fourth Lagrange point. Since no signal was detected, a 2σ upper limit was calculated resulting in a flux between 1 and 10 MeV of $\Phi = 5 \times 10^{-3}$ photons cm^{-2} s^{-1} (more than two orders of magnitude above the flux predicted by Phinney **et al.** 1988), with the corresponding limit to the luminosity in a 14 minute interval of $L_\gamma(1\,MeV < E_\gamma < 10\,MeV) = 1.1 \times 10^{33}$ erg s^{-1}. Comparison with equation (1) shows that this luminosity is slightly larger than the available spin-down power.

III. Discussion

This new detection of possible orbital modulation from PSR 1957+20 in the 50 MeV to 3 TeV gamma-ray band accentuates the special status of this object as the only binary radio pulsar showing various modes of orbital modulation from the radio through the optical and now possibly to the TeV gamma-ray bands. Unfortunately the Compton telescope was not sensitive enough to detect this effect and extend the radiation band still further. Assuming a power law dependence of the photon flux, the two flux measurements may be combined as follows:

$$F_\gamma(>E) = 4.3 \times 10^{-7} E_{GeV}^{-1} \text{ photons cm}^{-2}\text{ s}^{-1}. \qquad (2)$$

The flux limit for TeV radiation from L_5 is comparable to the detected flux for L_4, so that no firm conclusion regarding L_5 may be drawn yet. From the optical observations made by Callanan, Charles and van Paradijs (1989) it is also possible that TeV gamma-rays can be expected from the radio eclipse region due to inverse Compton scattering of electrons with energy $E > 1$ TeV on soft photons from the heated companion. Since our TeV gamma-ray detection technique is limited to signals with duration much less than 1 hour (the duration of the eclipse), this radiation, if present, would not be identified.

Although the L_4 and L_5 positions are gravitationally stable due to the small mass ratio of the white dwarf and neutron star, it may be expected that any material at this position will be dissipated by the pulsar wind but replenishment from the companion wind may cancel this effect. This is only possible for material flowing in tighter orbits than the white dwarf orbit, resulting in accretion onto L_4. The deduced capture time of 14 minutes calculated from the TeV measurements implies a radius $s \sim 10^{10}$ cm for the "Trojan matter" at L_4. This material will be gravitationally bound against radiation pressure if the corresponding column depth $2s\rho >> 4 \times 10^{-3}$ g cm^{-2}. Since no optical detection of L_4 was made it is probable that the inverse Compton process will not be able to produce TeV gamma-rays in the "Trojan matter", so that the only process then possible is acceleration by a shock formed near L_4. If we assume the formation of a shock, proton acceleration may take place at this small shock (radius $\simeq s$) to energies $E_{max} \simeq 20(s/10^{10}cm)$ TeV (see e.g. Harding 1990). Gamma-rays may then be produced through π^0 decay, formed in proton-proton collisions, provided

$2s\rho \simeq 50$ g cm^{-2}. The differential spectral index of 2 from equation (2) is also compatible with the acceleration of protons in a shock with a compression ratio of $r=4$. Equation (2) should then be valid, at least, from 70 MeV up to the maximum energy obtainable from the shock acceleration at L_4. The total gamma-ray luminosity from 70 MeV to 3 TeV should then be $L_T = 2.5 \times 10^{32}$ erg s^{-1}. Comparing this result with equation (1), the corresponding total conversion efficiency of the spin-down power to gamma-rays is $\eta_\gamma = 0.36f^{-1}$, which is an acceptable value given also the fact that no optical emission has been detected from L_4. Supporting the credibility of this result is the fact that the fluxes measured by Potchefstroom and COS-B compare very well with those predicted by Harding (1990) for the energy ranges $E_\gamma > 100$ MeV and $E_\gamma > 1$ TeV. Recently, Acharya **et al.** (1990) presented preliminary results on L_4, obtained with a similar telescope as that of Potchefstroom but at an energy of 4.3 TeV. Their upper limit of 1.9×10^{-10} photons cm^{-2} s^{-1} is a factor two larger than that predicted by equation (2). We therefore conclude that all available results are consistent with our measurements.

The non-detection of any radio dispersion delays at L_4 implies that the matter is not directly between us and the pulsar. Since the material will be in dynamic equilibrium, no significant magnetic field is expected at L_4 and the shock (with radius s) will be very close to the "Trojan matter". Accelerated particles can then be scattered into the line of sight. This scenario is acceptable in a system such as PSR 1957+20 if the orbital inclination is less than 87°. Since the maximum particle energy (Harding 1990) $E_{max} \propto s$, we may expect the signal to be more variable at TeV energies than at $E_\gamma > 70$MeV due to possible changes in s with time. This may result in $E_{max} \leq 1$TeV and hence a non-detection of TeV gamma-rays if s becomes too small.

Averaged over the whole orbit, repeated follow-up observations by telescopes such as GRO will be needed to improve the present upper limit: the COMPTEL sensitivity limit between 1 and 30 MeV will be about 5×10^{-5} photons cm^{-2} s^{-1} and that of EGRET between 50 and 150 MeV will be about 3×10^{-7} photons cm^{-2} s^{-1} for a 2 week observation period. Finally, if the observed orbitally modulated emission is real, EGRET will detect it with exceedingly high significance even in only one observation of the region including PSR 1957+20.

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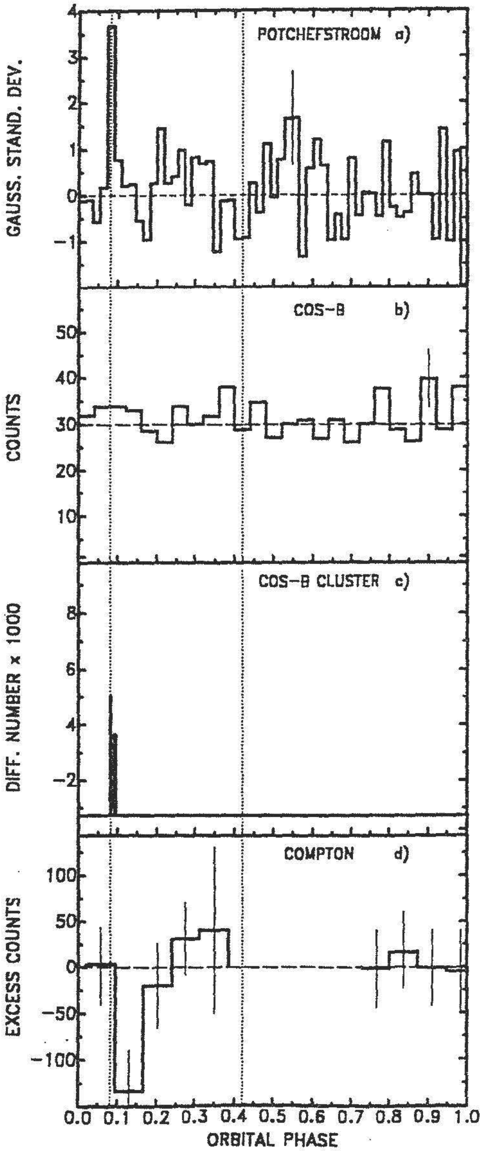
Figure captions

Figure 1: Distribution of σ_i for each 10-minute interval. The expected Gaussian distribution (smooth curve) is also shown.

Figure 2: Orbital phasograms of the events detected by the three gamma-ray telescopes from the direction of PSR 1957+20: (a) Significance (in terms of combined Gaussian standard deviations) of the excess counts from the Potchefstroom air Cerenkov telescope, (b) COS-B counts per bin, (c) COS-B photon density distribution as derived from the cluster analysis, and (d) excess counts from the Compton telescope. L_4 and L_5 are indicated by the dotted lines. Pulsar eclipse is centred at phase 0.25.

Figure 3: A Kernel density estimator (see De Jager **et al.** 1986) applied to the strongest observation of L_4. The dotted vertical lines indicate the center positions of the COS-B clusters. The background fit is shown by the dashed line.

Figure 2



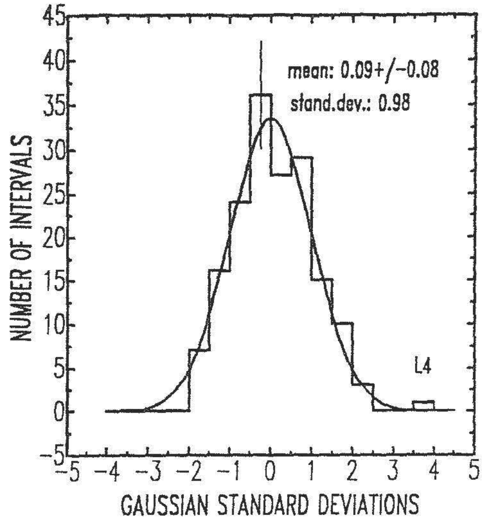


Figure 1

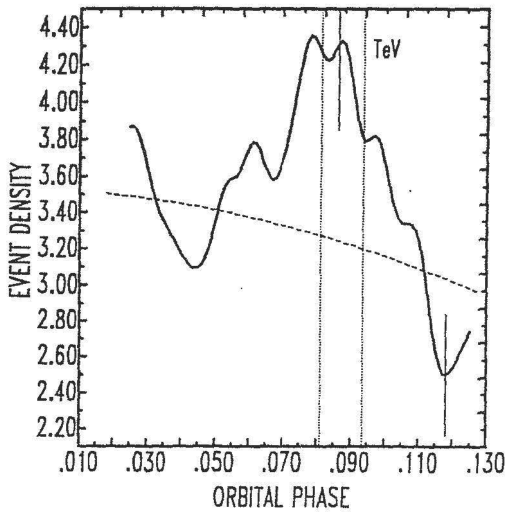


Figure 3