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MAGIC as a detector for 10 - 30 GeV pulsations from EGRET pulsars.

V. Fonseca[1], **M. Lopez-Moya**[2,1], **O.C. de Jager**[2], **C. Baixeras**[3], **V. Delgado**[1], **C. Domingo**[3], **L. Font**[3], **A. Ibarra**[1], **E. Ona**[2,1], **and A. Torres**[3]

[1]Physics Department, Univ. Complutense, 28040 Madrid, Spain
[2]Unit for Space Physics, Potchefstroom University, Potchefstroom, 2520, South Africa
[3]Physics Department, Univ. Autonoma Barcelona, 08l92 Barcelona, Spain

Abstract. The MAGIC telescope with its large mirror reflecting area has the capability to trigger on 10 GeV cosmic γ-rays, and with a collection area which increases rapidly with increasing energy, MAGIC should be able to overlap with EGRET in the 10 - 30 GeV range and capture pulsed γ-rays in the non-imaging mode. Shower size- and distance cuts should retain γ-rays below 30 GeV, while rejecting cosmic ray showers of higher energy and distances outside the low energy γ-ray trigger area. For a final background rate of 50 Hz or less, pulsed detections should be possible within a few hours. Crab and PSR B1951+32 have spectra extending possibly to at least 30 GeV, and since they transit near La Palma, the pulsed emission from these sources should prove that MAGIC can trigger in the 10 - 30 GeV range and will be useful for further calibration and understanding the operation at threshold. Some hard-spectrum unidentified EGRET sources may also be pulsars, and if their spectra extend to the 10 - 30 GeV range, searches for pulsations would be possible, which would make a discovery of high-dispersion/off radio beam γ-ray pulsars a possibility. The constraint for this capability is the detection within a single night, with confirmation runs the following few nights.

1 Introduction

EGRET observations of pulsars have shown that pulsar γ-ray spectra are typically harder than E^{-2}, and with the collection area of any Cerenkov telescope which increases rapidly with increasing energy, relatively large signal-to-noise levels are expected if these spectra extrapolate towards the VHE domain. However, the pulsar cutoffs expected in the GeV domain constrain detectors to have large reflecting areas and high PMT quantum efficiencies. In fact, both polar cap (Daugherty & Harding 1996) and outergap models (Hirotani 2001) predict that the EGRET synchrotron spectra should cut off at energies between a few GeV and a few tens of GeV. The strength of the cutoff is then determined by the absorption process in the pulsar magnetosphere: In the case of polar cap emission, magnetic pair production results in a very sharp cutoff, whereas the photon-photon pair production process in outergaps results in slower cutoffs (Nel & de Jager 1995).

Whereas the pulsar cutoffs for conservative polar cap models scale as (Nel & de Jager 1995; de Jager et al. 2001)

$$\frac{dN_\gamma}{dE} = K\left(\frac{E}{E_n}\right)^{-\Gamma} exp(-(E/E_o)^b). \qquad (1)$$

with $b \geq 1$, we find that K for EGRET pulsars are typically large, so that it is desirable to push the trigger threshold as low as possible. If h_T is the photo-electron threshold, then, to first order, we find that the integral cosmic ray background typically scales as $h_T^{-1.7}$ and the accidental triggers due to the NSB scales as $\sim h_T^{-4}$ (with the exact exponent depending on the trigger logic). If h_T corresponds to an energy just above E_0 (which lies between 5 GeV and 40 GeV - de Jager et al. 2001; see also Table 1), then the signal to noise ratio rises faster than the NSB as the threshold is reduced, until the effective threshold is just below E_0. This holds especially for a very bright pulsar such as Geminga, which is known to have a large value of K, $E_0 \sim 5$ GeV, and $b \sim 2.2$. The only limit then is the constraints imposed by the data acquisition system. This type of operation is then called the $pulsar\ mode$, as opposed to the normal imaging mode operating at higher thresholds.

Based on the collection efficiencies calculated by Barrio et al. (1998), De Jager (1998) showed that MAGIC can detect pulsations from EGRET pulsars in the 10 - 30 GeV range. E. Lorenz (1998, personal communication to O.C. de Jager) then suggested a size- and distance cut on background showers, while retaining γ-rays below ~ 30 GeV.

2 The Pulsar Sky Above 10 GeV

Thompson (2001) have shown EGRET pulse profiles above 100 MeV and above 5 GeV: whereas the pulse profiles of Crab, Vela, Geminga and PSR B1706-44 show typically two peaks per rotation, we find that the second peak for Crab,

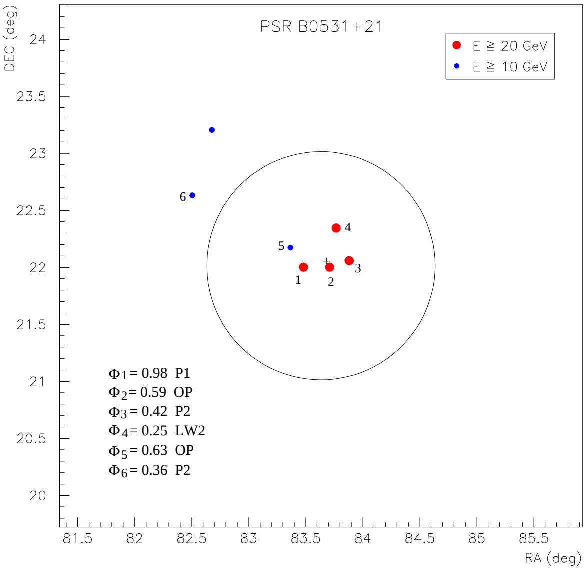

Fig. 1. A $\sim 4^\circ \times 4^\circ$ area of the γ-ray sky above 10 GeV around Crab. The cross denotes the position of the Crab pulsar and the solid circle the 95% acceptance area for photons above 10 GeV relative to the Crab. Each photon is indicated by a solid circle, with the circle size corresponding to the energy (see legend). The pulsar phase identification is as follows: (P1 - first peak; P2 - second peak; LW2 - leading wing 2; OP - offpulse).

Vela and Geminga becomes a significantly dominant feature above 5 GeV, whereas the first pulse for PSR B1706-44 becomes dominant. The pulse profile shape above 5 GeV may also resemble the expected profiles for MAGIC operating in the pulsar mode.

We have pressed the limits of EGRET even further by plotting individual sky photons above 10 GeV, where the effective collection area for MAGIC is already near a hundred square meter, which is already orders of magnitude larger than the corresponding collection area of EGRET, but at the cost of a high background relative to EGRET.

Figure 1 shows a skymap of the Crab region above 10 GeV. Five, possible six photons are associated with the Crab (numbered 1 through 6). The 5 GeV peak reported by Thompson (2001) extends between the leading wing of peak 2 (LW2), through peak 2 (P2). In this region we possibly see three pulsed photons associated with the LW2+P2 structure, consistent with the interpretation derived from the $E > 5$ GeV pulse profile.

Figure 2 shows a similar picture for PSR B1951+32, but with only two photons in the 95% confidence circle for 10 GeV γ-rays. The phase difference between the two photons is 0.02, and both are associated with the sharp second pulse (P2), consistent with Fierro (1996). The third photon is marginally consistent with both the point spread function and the edge of P2. The two or possibly three pulsed photons are the result of the claim of an unchanged spectrum between 100 MeV and 30 GeV. Thus, Crab and PSR B1951+32 may have a similar pulsed brightness above 10 GeV, whereas PSR B1951+32 is much weaker compared to the Crab near 100 MeV, which is a result of the harder spectrum of PSR B1951+32. Crab and PSR B1951+32 will be prime candidates for MAGIC (pulsar mode) given their optimal declinations relative to the latitude La Palma.

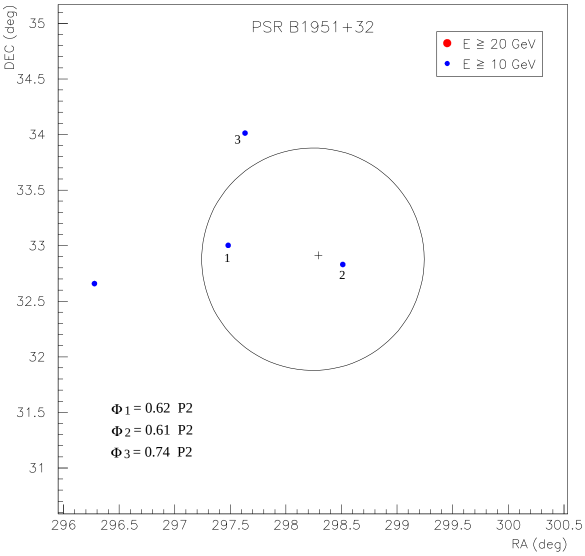

Fig. 2. A skymap of photons above 10 GeV around the position of PSR B1951+32 with the corresponding 95% confidence circle for 10 GeV photons relative to the pulsar (similar to Figure 1). The pulsed photon phases are consistent with the second peak (P2) as indicated.

Halpern et al. (2001) and D'Amico et al. (2001) discovered three energetic radio pulsars associated with unidentified GeV sources. These sources are also associated with X-ray sources (Roberts, Romani & Mallory, 2001), which confirm the trend that all EGRET pulsars are also X-ray sources. GeV J1837-0610 has the hardest spectrum (photon index -1.82 ± 0.14) and appears to be associated with the newly discovered 96 ms period pulsar PSR J1837-0604, and would transit La Palma at a zenith angle of 34 degrees. The $>$ 10 GeV photons around this pulsar is shown in Figure 3 and we find five photons within the 95% confidence circle (solid circle) for photons above 10 GeV from this pulsar. Note however that the background for this region of the sky is about double the corresponding γ-ray background for PSR B1951+32. The 95% positional uncertainty of the unidentified EGRET source (all energies down to 100 MeV - dashed circle) is within the solid circle. The star to the left of the EGRET source is G26.0+0.1, which is most likely an HII region at the same distance (6 kpc) as the pulsar (D' Amico et al. 2001). If the EGRET source is unpulsed, then it may be possible to explain the hard EGRET spectrum as relativistic bremstrahlung and inverse Compton emission by pulsar wind electrons on the dense HII material and IRAS infrared photons.

In Figure 3 we see a cluster of events around the approximate position (RA; Dec) $\sim$ (279.8°; -7.2°). This position is shifted relative to the 95% confidence contour of the unidentified EGRET source, which is consistent with the claim that the EGRET source is somewhat confused. There is also no

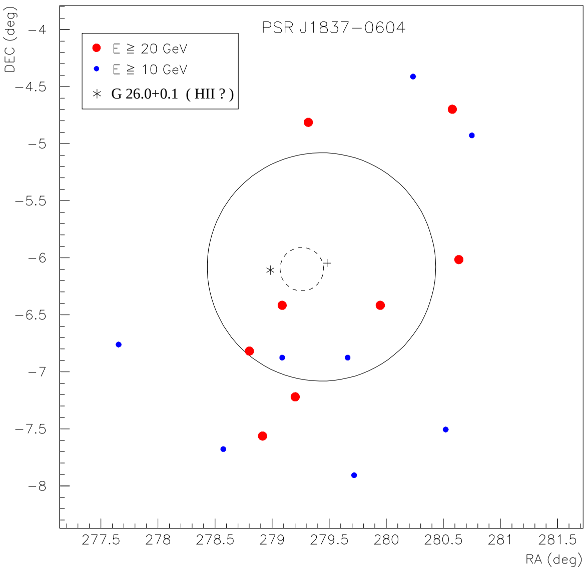

Fig. 3. A skymap of photons above 10 GeV around PSR J1837-0604 (cross). Solid circle: 95% confidence circle for arrival of 10 GeV photons relative to the pulsar. Dashed circle: 95% confidence circle for the location of 3EG 1837-0606 (for $E_\gamma > 100$ MeV.) Star: location of HII region G26.0+0.1 ($30' \times 15'$ shell).

supernova remnant within 1.5 degrees from the pulsar (D'Amico et al. 2001). An interesting (speculative) possibility is that this is another high dispersion pulsar (given the massive star formation environment) yet undetected in radio (maybe also due to beaming). In theory we do expect middle-aged pulsars with a low multiplicity for magnetic pair production, so that the mean photon energy is above 10 GeV (A.K. Harding, 2000, Personal Communication). A search for EGRET point sources above 10 GeV would be of interest from this perspective and a 10 GeV catalogue would show concentrations of a few photons amongst a low background.

3 MAGIC Detection Rates for EGRET Pulsars.

Following the procedure described by de Jager et al. (2001), we model the pulsar spectra above 1 GeV as a power law times an exponential cutoff with cutoff energy E_0. The strength of the cutoff is determined by the index b as given by Eqn (1). The most conservative estimate for the detection sensitivity is to take $b > 1$, consistent with magnetic pair production above the polar cap, whereas a value of $b < 1$ will yield a very optimistic detection rate. The constant K in Eqn (1) represents the monochromatic flux at the normalising energy $E_n \ll E_o$. We will normalise spectra at E_n near 1 GeV.

The γ-ray rate is calculated from the collection area vs energy $A(E)$ giving a γ-ray pulsed rate

$$R_p = \int \frac{dN_\gamma}{dE} A(E) dE \qquad (2)$$

The collection area for MAGIC was calculated for a special ring of 30% QE PMTs. Four-nearest neighbor pixels were used in the trigger after adding the NSB. We find that $A(E) \sim 100$ m^2 for $E \sim 10$ GeV. The background rate B was calculated *assuming incident cosmic ray showers for all energies at large accpetance angles relative to the pointing direction and core positions relative to the telescope, until convergence in B is seen.* The background rate $B \sim 200$ Hz.

Following the description (and pulsar parameters) by de Jager et al. (2001), we calculate the basic scaling parameter $x = p\sqrt{N}$, which holds for any test for uniformity on a circle (after folding the arrival times with a test period). The pulsed fraction is $p = R_p/(B + R_p)$ and the total number of events is given by $N = (R_p + B)T$, with T the observation time. Assuming that a single sharp peak (typically P2 for Crab and PSR B1951+32), with a duty cycle $\delta = 5\%$ survives above 10 GeV, the Z_m^2-test with number of harmonics $m = 1/(2\delta) = 10$ (de Jager, Swanepoel & Raubenheimer 1989) should be optimal. The expected value of the statistic is $< Z_m^2 >= x^2\Phi + 20$, where $\Phi = 5.8$ is derived from a Gaussian with a 5% FWHM (de Jager et al. 2001).

If we want to search for a new pulsar in a $T = 6$ hour run in a frequency interval of Δf (1 to 30 Hz), the factor of oversampling would be $\eta \sim 10$ per independent Fourier frequency (de Jager, Swanepoel & Raubenheimer 1989). The total number of independent trials would then be $M = \eta T \Delta f = 6.5 \times 10^6$. A DC excess of $x = 3\sigma$ above the sky background should give $< Z_{10}^2 >= 72$ for 20 degrees of freedom, which gives an average chance probability of 8×10^{-8}, or 0.5 after multiplying with all the trials. This should bury the true frequency amongst one of many candidate frequencies, which can be confirmed by one or two follow up observations the next few nights.

Table 1 shows the expected pulsed rates (for $x = 3$) and required observation times T_{200} ($B = 200$ Hz) and T_{50} ($B = 50$ Hz) for different pulsars. The arbitrary rate of $B = 50$ Hz assumes some degree of background rejection based on a size- and distance cut, but detailed simulations are required to determine the best rejection factor against background. The only purpose of showing T for two background rates is to show how this time scales with the background.

From Table 1 it is clear that we have to reach a background rate of less than 50 Hz after making suitable size- and distance cuts, so that a detection of Crab and PSR B1951+32 can be realised within one night. These two pulsars also transit close to La Palma, so that the minimum threshold energy can be realised at transit.

4 Conclusions

The construction of a 17 meter class telescope such as MAGIC allows the detection of showers induced by γ-rays as low as 10 GeV, which is in the domain of the EGRET instrument. Whereas the energy region above 30 GeV is still uncharted, there is a small energy window of overlap with EGRET (10 - 30 GeV), but MAGIC will be constrained to the non-imaging mode in this energy region. The fine pixelization and pulse height information should allow some rejection of background

Table 1. Gamma-ray spectral parameters above 1 GeV and corresponding MAGIC rates and observation time for detection. See de Jager et al. (2001) for spectral references.

Object	k ($\times 10^{-8}$) (cm^{-2}s^{-1}GeV^{-1})	Γ	E_o (GeV)	b	$F(>1$ GeV$)$ (cm^{-2}s^{-1})	R_p (hour^{-1})	T_{50} (hours)	T_{200} (hours)
Crab	24.0	2.08	30	2	22	730	3	12
Vela	138	1.62	8.0	1.7	148	500	7	26
Geminga	73.0	1.42	5.0	2.2	76	30	10^3	10^4
PSR B1951+32	3.80	1.74	40	2	4.9	530	6	24
PSR B1055-52	4.00	1.80	20	2	4.5	130	100	400
PSR B1706-44	20.5	2.10	40	2	20	870	2	9

events based on size- and distance cuts.

The pulsed spectra of Crab and PSR B1951+32 extrapolate to energies above 10 GeV (although with large errors), which should allow a detection within a few hours if the background can be reduced to 50 Hz. Investigating the sky maps of these pulsars above 10 GeV, we see that this conclusion is based on the existence of no more than 2 or 3 EGRET pulsed photons above 10 GeV from each of these sources, but buried in a very low 10 GeV background rate. In the case of Geminga we have shown that it is maybe impossible to detect any pulsed radiation given the fast cutoff of the pulsed spectrum below 10 GeV. However, the Geminga skymap above 10 GeV also shows only two pulsed photons (Fierro 1996), which would, by analogy, also imply a detection within one night! The long observation time for Geminga is a pathological effect of multiplying a spectrum dropping like a wall with a collection area rising similarly like a wall, and if the two walls do not overlap, the expected rate is zero requiring infinite observation time, whereas a slight reduction in threshold energy would allow the two walls to coincide in energy. Thus, in theory, Geminga may also be detectable within a single night under ideal conditions, provided that the trigger can be driven into the night sky background, and if the rejection against background cosmic ray showers (size- and distance cuts) can be managed at a hardware level.

Finally, some unidentified EGRET sources may also be detectable if they are pulsed, and a quick look at the area around PSR J1837-0604 shows that the hard-spectrum EGRET source position appears to shift southwards for $E > 10$ GeV, which may be due to the known source confusion for this source. More investigation is required to see if this is another high (radio) dispersion pulsar in a region of massive star formation, in which case the spectrum may extend comfortably into the MAGIC energy range.

References

Barrio, J.A. et al. 1998, MPI-PhE/98-5

D'Amico, N. et al. 2001, ApJ, 552, L45.

Daugherty, J.K. & Harding, A.K. 1996, ApJ, 458, 278.

de Jager, O.C., Swanepoel, J.W.H. & Raubenheimer, B.C. 1989, A&A, 170, 187.

de Jager, O.C. 1998, in Proc. 16th ECRS, ed. J. Medina, University of Alcalá, 311.

de Jager, O.C., Konopelko, A., Raubenheimer B.C., & Visser, B. 2001, in Proc. International Symposium, Heidelberg 26-30 June 2000, Germany, Eds. F.A. Aharonian, H.J. Völk American Institute of Physics 558, 613.

Fierro, J.M. 1996, *Observations of Spin-Powered Pulsars with the EGRET Gamma Ray Telescope*, Ph.D. Thesis (Stanford University), unpublished.

Halpern, J.P. et al. 2001, ApJ, in press.

Hirotani, K. 2001, ApJ, 549, 495.

Lamb, R.C. & Macomb, D.J., 1997, ApJ, 488, 872

Nel, H.I. & de Jager, O.C. 1995, Astr. Space Science, 230, 299.

Roberts, M.S.E., Romani, R.W., & Kawai, N. 2001, ApJS, 133, 451.

Thompson, D.J. 2001, in Proc. International Symposium, Heidelberg 26-30 June 2000, Germany, Eds. F.A. Aharonian, H.J. Völk American Institute of Physics 558, 103.