Prospects of observing pulsed radiation from gamma-ray pulsars with H.E.S.S.

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Abstract. Observations and theoretical studies have demonstrated that the pulsed spectra of all gamma-ray pulsars terminate at energies below a few hundred GeV. In most cases we expect this cutoff energy $E_o$ to be around 10 GeV. Only with next-generation ground-based $\gamma$-ray telescopes, which are expected to have non-zero trigger probabilities near 10 GeV, can we expect to detect pulsations. The large $\gamma$-ray fluxes below $E_o$, together with the associated sharp pulse profiles, compensate for the lack of imaging capability near threshold. For H.E.S.S. we find that the pulsed component of PSR B1706-44 should be detectable near threshold, whereas the unidentified GeV EGRET sources should be detectable if the superexponential cutoff energy is larger than $\sim 30$ GeV for relatively hard pulsar photon spectra ($\sim E^{-1.5}$).

A Introduction

Whereas gamma-ray pulsars are known to count amongst the brightest sources in the 1 - 30 GeV range (Lamb & Macomb, 1997), only their plerions, supernova shells and extragalactic sources appear to be visible at TeV energies. This is not unexpected, since pulsed $\gamma$-rays are known to be created in strong magnetic fields and magnetic pair production results in a superexponential cutoff above a characteristic energy $E_o$. Simulations of pair cascades have shown that $E_o$ is usually in the 10 GeV region (Daugherty & Harding, 1996), but this cutoff depends on several parameters, such as the altitude of $\gamma$-ray production above the polar cap, the observer’s viewing angle relative to the spin axis, and the magnetic inclination angle relative to the spin axis. A $\gamma$-ray/e$^+/-$ cascade develops and those photons which escape pair creation (with $E < E_o$) are observable, resulting in a pulsed spectrum which is typically harder than $E^{-2}$ for $E < E_o$. Based on this consideration, Nel & de Jager (1995) modelled the high energy $\gamma$-ray pulsed spectra of pulsars as

\begin{equation}
\frac{dN_\gamma}{dE} = k(E/E_n)^{-g} \exp(-(E/E_o)^b).
\end{equation}
Whereas pulsar photon spectral indices between $g = 1.4$ and $2.1$ are observed, harder spectra are theoretically possible (A.K. Harding, 2000, personal communication to O.C. de Jager). The constant $k$ represents the monochromatic flux at the normalising energy $E_n \ll E_o$. We will normalise spectra at $E_n = 1$ GeV.

In the case of the outergap model for pulsars (Cheng, Ho, & Ruderman 1996), $\gamma$-ray production is expected to occur near the pulsar light cylinder, and the cutoff is expected to result from energetics arguments, rather than from magnetic pair production. In this case a larger $E_o$ may be observable. Ground-based TeV $\gamma$-ray observations however provide firm upper limits on $E_o$. (Nel et al. (1993) gave a detailed discussion on this topic; see also Catanese & Weekes 1999.)

## B Gamma-Ray Pulsar Spectral Parameters above 1 GeV

Table 1 shows the parameter results of a fit to the total pulsed spectra of the six brightest EGRET $\gamma$-ray pulsars. These spectral parameters reproduce the EGRET flux up to 30 GeV, and are consistent with the TeV pulsed limits. They also reproduce the GeV source catalog flux (Lamb & Macomb 1997). In the case of Vela and Geminga the cutoffs are well defined by the EGRET data and the errors on $E_o$ are relatively small ($\sim 20\%$). In the case of Crab and PSR B1055-52, some evidence of a turnover is seen in the spectra above 10 GeV, although it is difficult to obtain reliable measures of $E_o$ and $b$. In the case of PSR B1951+32 and PSR B1706-44 we see no evidence of a turnover up to 30 GeV, and a minimum value of $E_o = 40$ GeV (consistent with EGRET) was selected. This value is conservative with respect to the H.E.S.S. response. For those cases where $E_o$ is not well defined, we have selected $b = 2$ (a value typical for a spectrum attenuated by magnetic pair production) to give conservative H.E.S.S. rates.

Using the H.E.S.S. collection area vs. energy $A(E)$ for any 2-telescope triggers (Konopelko 2000), we were able to calculate the expected rates $R_p$ for pulsed $\gamma$-rays by integrating the product of $A(E)dN_\gamma/dE$ over all energies. The results for the six EGRET pulsars are shown in Table 1 (indicated by “$R_p$”). It is clear that the rate for PSR B1706-44 is the largest of all pulsars if $E_o$ is not smaller than 40 GeV.

## C H.E.S.S. Sensitivity for Pulsed $\gamma$-Ray Mission

It was shown by de Jager, Swanepoel & Raubenheimer (1987) and de Jager (1994) that the basic scaling parameter for any test for uniformity on the circle (given a test period) is given by $x = p\sqrt{n}$, where $p = R_p/(R_b + R_p)$ is the pulsed fraction, with $R_p$ the pulsed rate and $R_b$ the background rate. The total number of events is given by $N = (R_p + R_b)T$, with $T$ the observation time. In this case the test statistic for uniformity for the general Beran (1969) class of tests is given by $B = x^2\Phi_B + c$, where $\Phi_B$ is derived from the intrinsic pulse profile, and $c$ is the noise term. It was shown by Thompson (2000) that the pulse profiles above 5 GeV consist mostly of a single narrow peak, and it can be shown that $\Phi_B = 5.8$ for a 5%
TABLE 1. Gamma-ray spectral parameters above 1 GeV and corresponding H.E.S.S. rates and observation time for detection. Spectral references from Macomb & Gehrels (1999).

| Object          | $k \times 10^{-8}$ | $g$  | $E_o$ (GeV) | $b$  | $F(>1$ GeV) (cm$^{-2}$s$^{-1}$) | $R_p$ (hour$^{-1}$) | $T$ (10-hour days) |
|-----------------|---------------------|------|-------------|------|-------------------------------|--------------------|--------------------|
| Crab            | 24.0                | 2.08 | 30          | 2    | 22                            | 100                | 3                  |
| Vela            | 138                 | 1.62 | 8.0         | 1.7  | 148                           | 8                  | 400                |
| Geminga         | 73.0                | 1.42 | 5.0         | 2.2  | 76                            | $\ll 1$            | -                  |
| PSR B1951+32    | 3.80                | 1.74 | 40          | 2    | 4.9                           | 180                | 1                  |
| PSR B1055-52    | 4.00                | 1.80 | 20          | 2    | 4.5                           | 8                  | 420                |
| PSR B1706-44    | 20.5                | 2.10 | 40          | 2    | 20                            | 240                | 1                  |

FWHM (single peak), if $B$ is taken as the $Z_m^2$ test statistic with $m = 10$ harmonics (see e.g. de Jager, Swanepoel & Raubenheimer 1987). In this case $c = 20$.

A value of $x = 3$ would introduce a $\sim 3\sigma$ DC excess in a spatial analysis, but assuming that we have no imaging capability for $E_o$ near the detection threshold, we have to rely on a timing analysis, which would give $Z_{10}^2 \sim 73$, or a chance probability of $7 \times 10^{-8}$ if the period is known, but 0.03 after multiplying with the number of trials for a 6 hour observation if searching for periods as short as 50 ms. A confirming run (e.g. on a second night) should always be made to see if one of the few most significant periods from the previous run have repeated itself - in this case at the $\sim 10^{-7}$ level.

Using an additional topological software trigger, and selecting events by image size and angular shape, we were able to reject $\sim 99.2\%$ of the triggered background events, while retaining 95% of the source events. From a total background rate of 1 kHz (Konopelko 2000), we get $R_b = 8$ Hz. This allows us to calculate detection sensitivities for periodicities:

From the GeV source catalogue, we find that the galactic unidentified EGRET source (some may be pulsars - Lamb & Macomb 1997) fluxes range from $F(>1$ GeV) = 1 to $25 \times 10^{-8}$ cm$^{-2}$s$^{-1}$. Figures 1 and 2 give the H.E.S.S. sensitivity for a wide range of possible pulsar photon spectral indices between 1 and 2, and requiring a marginal detection within $T = 3$ to 6 hours (assuming a minimum “DC significance” of $x = 3$): Figures 1 and 2 respectively show $E_o$ and $T$ vs $k$, with the latter within the EGRET range as discussed above. Table 1 also shows $T$ calculated in the same way, but assuming the spectral parameters of individual pulsars.

### D Conclusions

It is clear that H.E.S.S. can only detect pulsars if $E_o$ exceeds $\sim 30$ GeV. Even weak EGRET sources may be detectable if the spectra are as hard as $E^{-1}$, provided that $E_o$ exceeds the levels prescribed by Figure 1. PSR B1706-44 (for which $E_o$ is known to be at least as large as $\sim 40$ GeV) should be a H.E.S.S. candidate and
FIGURE 1. Figure 1 (Left panel): Parameter space ($E_o$ vs $k$) for the detection of unknown pulsars within one night with H.E.S.S. using a timing analysis approach, and assuming $x = 3$. The three curves represent (from bottom to top) photon spectral indices of 1, 1.5 and 2.0. The solid line is for 3 hours of continuous observation, whereas the dashed lines (for the same set of spectral indices) represent a six-hour run. Figure 2 (right panel): The observation time required to detect a pulsar as a function of $k$ for a photon index of 1.5 and $E_o$ as shown (also for $x = 3$).

other similar pulsars (such as PSR B1951+32) may be similarly detectable within one night. If one cannot detect a clear signal within a single night, an exact timing solution would be required to do a coherent analysis over a long period of time.

Whereas we have addressed the conservative polar cap model, any outergap component is expected to give a large value for $E_o$ (which is no challenge for H.E.S.S.), but $k$ may be small for such pulsars. This will be treated in a separate paper.

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