

Limits on pulsar parameters for pulsed detections with H.E.S.S.

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Abstract. The non-detection of pulsed sub-TeV γ -rays from EGRET pulsars proves that the EGRET pulsed spectra of all γ -ray pulsars should terminate at energies below a few hundred GeV. The spectrum of a typical integrated pulse profile predicted by the polar cap model resemble typically a hard component, followed by a super exponential cutoff between 1 MeV (PSR B1509-58) and tens of GeV (e.g. Crab, PSR B1951+32 etc). Outergap models predict a hard low flux component extending to TeV energies, and the stereoscopic property of the H.E.S.S. (High Energy Stereoscopic System) ground-based detector (under construction) would have the advantage to discriminate against the background above 50-100 GeV, so that such a second component may be detectable. However, the challenge posed for any ground-based γ -ray detection is to prove that the instrument can detect a pure polar cap origin, whereas an outergap mechanism would provide little challenge given the rapid increase in the effective area $A(E)$ with increasing energy E for Cerenkov telescopes.

Using a topological trigger in the non-imaging mode, we show that H.E.S.S. should be able to detect pulsed emission from PSR B1706-44 within a few hours if the cutoff energy is above 30 GeV as suggested by EGRET observations. The recently detected radio pulsar PSR J1837-0604 (pulsar period: 96 ms) associated with the unidentified EGRET source GeV J1837-06010 should also be detectable within a few hours if the source is pulsed and if its cutoff is similar to that of PSR B1706-44. H.E.S.S. should even be able to image middle-aged, low-multiplicity pulsars for which the mean photon energy is expected to be well above 10 GeV. Such observations should provide important constraints on the final evolutionary status of γ -ray pulsars and millisecond pulsars in general.

1 Introduction

Basic pulsar electrodynamics involves a definition of the open field lines, which close outside the light cylinder, so that a polar cap potential drop $\Delta V \propto B_s/P^2$ is in excess of 10^{12} eV, where B_s is the surface field strength and P the pulsar period. The Goldreich Julian pulsar current from the polar cap scales similarly as $I_{GJ} \propto B_s/P^2$, and is responsible for the extraction of electrons and possibly Fe ions from the surface of the polar cap, where a component of the electric field parallel to \mathbf{B} exists. The product of ΔV and I_{GJ} is then comparable to the magnetic dipole spindown power.

It is therefore natural to follow the curvature γ -ray emission from accelerated electrons above the polar cap, resulting in a cone-like beam of γ -ray emission above the polar cap until magnetic pair production no longer dominates the pair production process. Daugherty & Harding (1996) were able to reproduce the observed pulse profiles and spectra for such processes, but a natural consequence of the polar cap process is a super exponential cutoff of the spectrum as discussed by Nel & de Jager (1995).

In competition with the polar cap model, is the so-called outergap model, whereby a potential drop may develop around the $\mathbf{\Omega} \cdot \mathbf{B} = 0$ “null surface”, which is at a much larger distance from the pulsar compared to the polar cap emission region. Spectra can be self-consistently derived for outergaps (Hirovani 2001), but it remains to be shown how the outergap geometry can be unified with the electrodynamics. In this case we find that photon-photon pair production and the available acceleration potential determines the cutoff. Both a synchrotron and a much higher energy inverse Compton component can then escape from the outergap to the observer.

A generic model (polar cap and/or outergap) for the tails of pulsed differential spectra is then given by

$$\frac{dN}{dE} = K_1 E^{-\Gamma_1} \exp(-(E/E_1)^b) + K_2 E^{-\Gamma_2} \exp(-(E/E_2)^c)$$

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The second component would be absent in the case of pure polar cap γ -ray emitters, with the additional signature of a super exponential cutoff ($b \geq 1$ and $K_2 = 0$). An outergap origin can be interpreted in terms of a non-zero K_2 , but with slower rollovers compared to polar cap models, since the outergap absorption process is controlled by photon-photon pair production, which has a weaker energy dependence compared to magnetic pair production.

Timing and spectroscopic observations in the 10 GeV to 10 TeV region can therefore discriminate between such models, and GLAST is expected to play a key role in this regard, but next generation telescopes such as H.E.S.S., MAGIC and CELESTE, STACEE (at their full capacity) should be able to steal some of the limelight in the meantime, with H.E.S.S. and CANGAROO IV, VERITAS in the best position to test outergap models above 50-100 GeV, given their stereo capability for efficient background rejection.

2 Gamma-Ray Pulsar Parameters

To obtain conservative estimates for the detection rate, we have to employ the most conservative model. We therefore assume that the polar cap mechanism is responsible for the pulsed γ -ray emission, so that our generic model reduces to a single component:

$$dN_\gamma/dE = K(E/E_n)^{-g} \exp(-(E/E_o)^b). \quad (1)$$

Whereas pulsar photon spectral indices between $g = 1.4$ and 2.1 are observed, harder spectra are theoretically possible for middle-aged pulsars (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 near 1 GeV.

It was shown that the total γ -ray pulsed luminosity L_γ (pulsed) scales roughly with the Goldreich Julian pulsar current B_s/P^2 , which, in turn, is proportional to $\dot{E}^{1/2}$, with \dot{E} the spindown power. Neglecting the differences in the spectral index and cutoff energies, we even find that the normalization constant K (in units of $\text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}$) at 1 GeV scales with basic pulsar parameters: Fitting K as a power law function of the spindown power, we find (normalised to the EGRET pulsars):

$$K = 10^{-17.8} (\dot{E})^{0.305} (d_{\text{kpc}})^{-2} \quad (2)$$

The spindown power is in units of ergs/s. It is interesting to notice that Vela and PSR B1706-44 (with similar values for \dot{E}) give the largest scatter as a result of their significant differences in flux and distance. In fact, beaming and line-of-sight effects contribute to the large scatter.

Whereas the total γ -ray pulsed flux scales with pulsar current $I_{\text{GJ}} \propto \dot{E}^{1/2}$, we therefore find that the GeV flux (or luminosity), to a first order, scales as

$$L_\gamma(\text{GeV}) \propto (I_{\text{GJ}})^{0.6} \quad (3)$$

This finding is in principle consistent with the claim of Nel & de Jager (1995) that the mean photon energy increases

with increasing pulsar age. Thus, older (lower \dot{E}) pulsars become relatively brighter in the GeV region, which explains the weaker dependence of the GeV flux on current (or spindown power). It is thus clear that ground-based γ -ray observations may have the best chance of detecting middle aged pulsars, provided that the beaming is favorable, the distance is not too large, and the cutoff energy is well above 10 GeV. All these constraints are reasonably within reach for future ground-based γ -ray observations.

3 Detection capability of H.E.S.S. for pulsars

De Jager et al. (2001) discussed the capability of H.E.S.S. (Hofmann et al (2001)) to detect pulsed emission from the EGRET pulsars, given the assumption of super exponential cutoffs as expected from polar cap emission. A detection within a single night (in general) restricts the number of independent frequencies to be searched, which enables the identification of a single unique frequency, or, at least a number of candidate frequencies which can be confirmed within a few days of follow up observations. We will copy the list of de Jager et al. (2001), but add the recent discoveries of radio pulsars associated with unidentified GeV EGRET sources.

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 γ -rays by integrating the product of $A(E)dN_\gamma/dE$ over all energies. The results for the six EGRET pulsars are also 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.

It was shown by de Jager, Swanepoel & Raubenheimer (1989) 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 Φ_B is derived from the intrinsic pulse profile, and c is the noise term. It was shown by Thompson (2001) that the pulse profiles above 5 GeV consist mostly of two narrow peaks, but given the spectral differences between the two peaks, we will assume that only a single peak survives at the highest energies, so that $\Phi_B = 5.8$ if we assume a 5% duty cycle, and $B = Z_m^2$ test statistic with $m = 10$ harmonics (see e.g. de Jager, Swanepoel & Raubenheimer 1989). 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 7×10^{-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

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	$k (\times 10^{-8})$ ($\text{cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}$)	g	E_o (GeV)	b	$F(> 1 \text{ GeV})$ ($\text{cm}^{-2}\text{s}^{-1}$)	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
PSR J2229+61	4.8	2.24	40	2	3.9	32	25
PSR J1420-60	6.9	2.02	40	2	6.9	110	2
PSR J1837-06	5.5	1.82	40	2	6.7	190	1

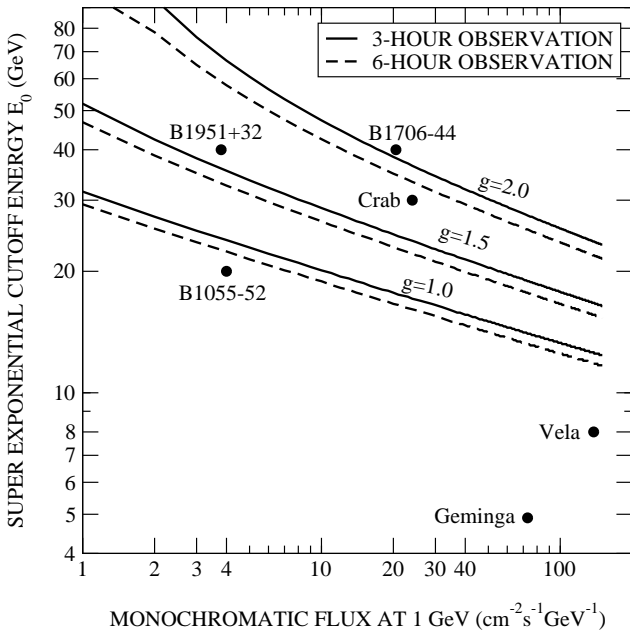


Fig. 1. Parameter space (E_o vs K) for the detection of unknown pulsars within one night with H.E.S.S. using a timing analysis approach, and assuming a DC excess of $x = 3$. The three curves represent (from bottom to top) photon spectral indices of 1, 1.5 and 2.0. The solid line is for 3 hours of continuous observation, whereas the dashed lines (for the same set of spectral indices) represent a six-hour run.

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, recently tested with the HEGRA system of 5 imaging atmospheric Cherenkov telescopes (Lucarelli et al. (2001)) 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 below 50 GeV. From a total background rate of about 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 fluxes of

the galactic unidentified EGRET source (some may be pulsars - Lamb & Macomb 1997) range from $F(> 1 \text{ GeV}) = 1$ to $25 \times 10^{-8} \text{ cm}^{-2}\text{s}^{-1}$. Figure 1 give the H.E.S.S. sensitivity for a wide range of possible pulsar spectral indices between 1 and 2, and requiring a marginal detection within $T = 3$ to 6 hours (assuming a minimum “DC significance” of $x = 3$). This figure also shows E_o vs K , with the latter within the EGRET range as discussed above. Table 1 also shows T calculated in the same way (in 10-hour shifts), but assuming the spectral parameters of individual pulsars. It is clear the H.E.S.S. will only be able to detect pulsed emission if E_o exceeds 30 GeV, which is realized at least for PSR B1706-44 in the Southern Hemisphere.

4 Three Young Pulsars Associated with GeV Sources

Halpern et al. (2001) reported on the discovery of an energetic pulsar PSR J2229+6114 (51.6 s), which appears to be associated with the GeV unidentified EGRET source GEV J2227+6101. D’Amico et al. (2001) also identified two pulsars associated with another two GeV EGRET sources: These are PSR J1420-6048 (68 ms) associated with GeV J1417-6100, and PSR J1837-0604 (96 ms) associated with GeV J1837-06010. Assuming that the excess EGRET photons from these GeV sources are pulsed, we have calculated the H.E.S.S. sensitivities for pulsed detections assuming a cutoff of 40 GeV as shown in Table 1. Since we do not know what the cutoff energy is, we also calculated the required observation time as a function of the cutoff energy for these two pulsars as shown in Figure 2.

The best candidate is PSR J1837-0604, and even for this pulsar we require a cutoff energy similar to that of PSR B1706-44 (as large as 30 - 40 GeV) if the pulsar is to be detected within one night of observations.

5 Conclusions

By operating H.E.S.S. in a non-imaging topological trigger mode, we can accept low energy γ -rays, while still rejecting $> 99\%$ of the background, which allows us to detect pulsa-

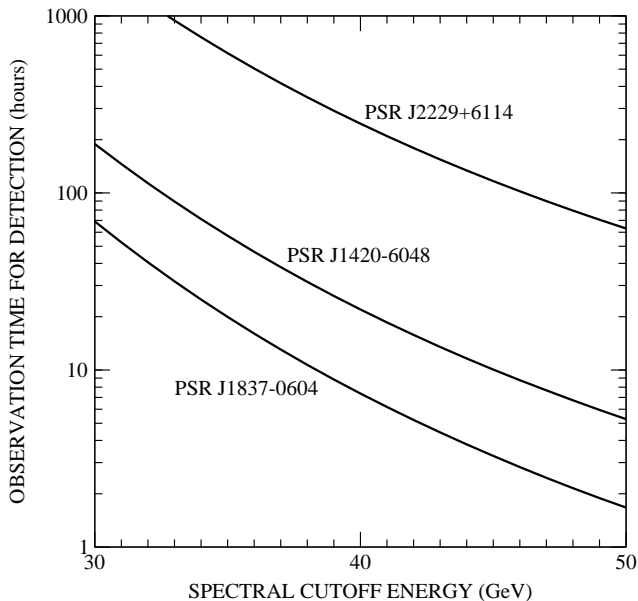


Fig. 2. The observation time required for a pulsed detection by H.E.S.S. as a function of the spectral cutoff energy E_0 for the three new radio pulsars associated with unidentified EGRET GeV sources. The γ -ray spectrum associated with each pulsar is given in Table 1. In each case it was assumed that the EGRET excess is 100% pulsed.

tions from pulsars if the spectral cutoff energy is above 30 GeV. This, added with the hardness of the spectra below the cutoff, makes a detection within one night possible for a few pulsars. We find that PSR B1706-44 should be the best candidate for the H.E.S.S. site in Namibia.

The detection of radio pulsars associated with unidentified EGRET sources improves our confidence that many hard-spectrum galactic EGRET sources may be due to pulsed emission from pulsars. We have discussed three recently detected radio pulsars, and we find that PSR J1837-0604 (being a hard GeV source) may also be detectable within a single night if the EGRET source is pulsed and if the cutoff is above 30 - 40 GeV. In fact, one may even be able to derive the period from a search in frequency if simultaneous radio observations are not available. It can be shown that a slight difference in cutoff energy can make an enormous difference in detection sensitivity: increasing the cutoff energy by a relatively small amount can change the situation from being a slave to radio information to that of determining radio parameters independent of radio information.

Finally, there is quite a large population of millisecond pulsars, and some of them are predicted to be γ -ray bright. Fierro et al. (1995) searched for such pulsars in the EGRET data base, but found non despite the availability of contemporary rotational parameters. Cascading above the polar cap is still required to produce the radio emission, and some of them show pulsed magnetospheric X-ray emission, which is indicative of accelerating potentials above the polar cap. One possibility is that the low magnetic fields associated with millisecond pulsars results in a relatively small cascading multi-

plicity, so that the mean photon energy which escapes from the polar cap is between 10 and 100 GeV - much closer to the primary curvature γ -ray energy compared to canonical high-B pulsars. H.E.S.S. should be able to image such sources above 50 GeV using its full stereo capability, and provide significant upper limits if a source is not seen.

Acknowledgements. The South African group acknowledges the financial contribution of the South African Department of Arts Culture and Science and Technology towards the H.E.S.S. project.

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