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Millisecond pulsars as VHE gamma-ray sources

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Abstract. The detectability of millisecond pulsars in VHE gamma-ray bracket (> 5×10^{11} eV), with the recently-commissioned TACTIC array, has been investigated on the basis of system energetics and the pulsar polar gap model. It is shown that, out of the 24 millisecond pulsars with known values of period, period derivative and distance, at least two millisecond pulsars qualify as potentially detectable by the TACTIC array above 0.5 TeV photon energy.

1. Introduction

The first ms pulsar, PSRB 1937+21, with a spin period of 1.55 ms, the fastest known millisecond pulsar till date, was discovered by Backer et al. (1982) and till now ~ 45 ms pulsars (defined as pulsars with spin periods ≤ 25 ms) have been discovered. It is generally believed that the ms pulsars are old ($10^8 - 10^9$ y), recycled pulsars resulting from accretion-driven spin-up processes and have weaker surface magnetic fields (~ $10^8 - 10^9$ G) as compared to the canonical pulsars (Alpar, 1982; Bhattacharya and van den Heuvel, 1991). The weak surface magnetic field is likely to allow the escape of very high energy (VHE) gamma-rays, generated in the polar cap region of these pulsars through the curvature radiation and other electromagnetic processes, without severe attenuation by magnetic pair-production interactions. Naturally, there is a possibility of some of the nearby ms pulsars being detectable as VHE gamma-ray sources. Here we examine the VHE detectability of ms pulsars with the recently-commissioned TACTIC Imaging Cerenkov Telescope at Mt. Abu (Bhat, 1997) and identify potential candidates on the basis of system energetics and in the framework of the polar-gap model (Usov, 1983).

2. System energetics

The model-independent VHE photon flux from a pulsar under the assumption that the VHE gamma-ray luminosity is derived from the rotational energy of the pulsar, can be written as :

$$F_\gamma(> E_\gamma)=\eta\dot{E}/4\pi f_\gamma g_\gamma d^2\bar{E}_\gamma \ photons\ cm^{-2}\ s^{-1} \qquad (1)$$

where $\dot{E}$ is the spin-down power of the pulsar (ergs s–1), $\bar{E}_\gamma$ is the mean gamma-ray energy in ergs, f_γ is the beaming factor, g_γ is the beam sampling factor, $d(cm)$ is the distance to the pulsar and η is the spin-down power to VHE gamma-ray luminosity conversion efficiency. In the absence of any direct information, we assume that the gamma-ray beam has a width of 1 steradian (f_γ=1/4π) and g_γ=1, implying that the detector is able to sample across the entire beam. For standard pulsar parameters, equation (1) can now be put as

$$F_\gamma(> 0.5TeV) = 2.89 - 10^{-3}\ \eta \dot{p}_{-15} p_{ms}^{-3}/d_{kpc}^2\ photons\ cm^{-2}\ s^{-1} \quad (2)$$

where $\dot{p}_{-15} = \dot{p}/10^{-15}$, $p_{ms} = p/10^{-3}$, $d_{kpc} = \frac{d(cm)}{3.08\times10^{21}}$, p is the pulsar period in seconds and $\dot{p}$ is the period derivative. It may be noted that in deriving equation (2), we have assumed that the VHE photons have an average energy of 1 TeV (corresponding to a threshold energy of 0.5 TeV for the TACTIC and a power-law spectrum with differential exponent ~ 2.5 for the source gamma-rays). The minimum detectable flux of the TACTIC array, for a 10σ signal in 100h of source observations, is 7 × 10^{-12} photons cm^{-2} s^{-1} above 0.5 TeV. The detectability condition can, therefore, be written as,

$$F_\gamma(> 0.5\ TeV) \geq 7 \times 10^{-12}\ photons\ cm^{-2}\ s^{-1} \quad (3)$$

Equations (2) and (3) can be rearranged to yield

$$\eta \geq 2.42 \times 10^{-9}\ d_{kpc}^2\ p_{ms}^3/\dot{p}_{-15} \quad (4)$$

Equations (4) has been used to calculate the limiting value of the VHE gamma-ray conversion efficiency needed to make the ms pulsar detectable with the TACTIC array. Fig. 1 shows a scatter plot of the estimated η values as a function of the pulsar period p. Since conversion efficiencies of η > 1% are physically unrealistic, we identify as potentially detectable only those ms pulsars for which η ≤ 1% (Pulsars lying below the horizontal line in Fig. 1). We

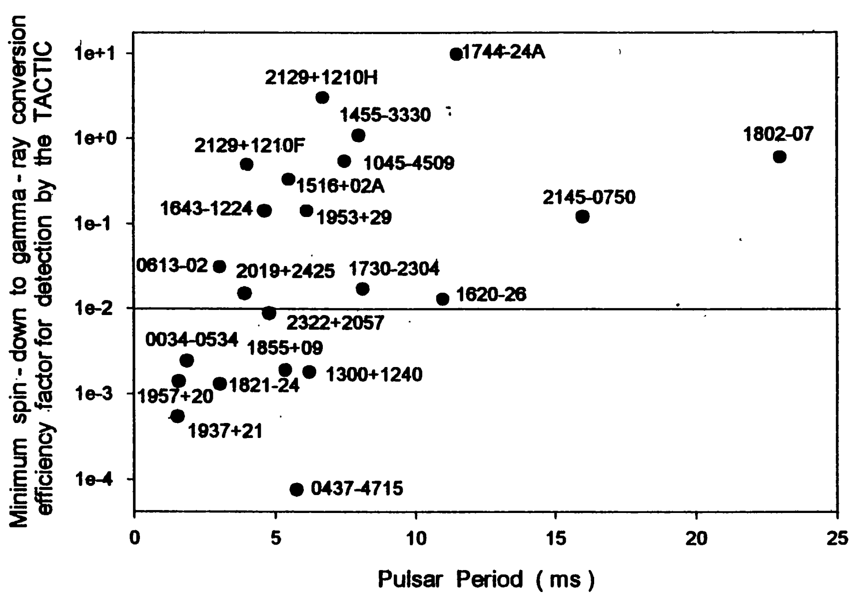

Figure 1. Plot of minimum spin-down γ-ray luminosity conversion efficiency η needed for a pulsar to be detectable with TACTIC as a function of pulsar period. Pulsars below the horizontal line (η=1%) are potentially detectable.

find that 7 ms pulsars, namely, PSRJ 0034–0534, PSRJ 1300+1240, PSRB 1821–24, PSRJ 2322+2507, PSRB 1855+09, PSRB 1937+21 and PSRB 1957+20, qualify this detectability criterion. PSRJ 0437–4715, one of the most probable sources energetically, cannot be observed from Mt. Abu.

3. Model considerations

Predictions of the VHE gamma-ray emission from isolated ms pulsars are generally based on the model proposed by Usov (1983) for the prototype ms pulsar PSRB 1937+21. According to this model, primary gamma-rays with energies larger than E_{max}, where

$$E_{max} \simeq 4 \times 10^{10}\, p_{ms}/B_{12} \simeq 851(p/\dot{p})^{1/2}\, eV \tag{5}$$

are absorbed due to magnetic pair-production interactions in the polar cap region, leading to a gamma-ray luminosity,

$$L_{\gamma}(E_{max}) = 3.4 \times 10^{31}[p^{-0.19} - B_{12}^{0.14}]B_{12}^{0.86}\, p^{-1.67}\, erg\ s^{-1} \tag{6}$$

where $B_{12} = B(G)/10^{12}$, B(G) being the surface magnetic field of the pulsar in Gauss. The corresponding VHE gamma-ray flux can be written as

$$F_{\gamma}(> 0.5TeV) = \frac{1.38 \times 10^{-6}}{d_{kpc}^2}\, p^{-1.43}\, \dot{p}^{0.43}(1 - 11.85\, p^{0.26}\, \dot{p}^{0.07})\ photons\ cm^{-2}\ s^{-1} \tag{7}$$

Equating $F_{\gamma}(> 0.5\ TeV)$ with the TACTIC minimum detectable flux, we can write the detectability condition as

$$p^{-1.43}\, \dot{p}^{0.43}(1 - 11.85\, p^{0.26}\, \dot{p}^{0.07}) \geq 5.07 \times 10^{-6}\, d_{kpc}^2 \tag{8}$$

The quantity in the brackets is a slowly varying function of p and almost independent of $\dot{p}$ and has a value in the range 0.9 to 0.75 for periods in the range of 1-25 ms and $\dot{p}$ in the range 10^{-18} to 10^{-20}. We adopt a constant value of 0.8 for this factor and transform the detectability condition to

$$\dot{p}_{-15} \geq 9.57 \times 10^{-8}\, p_{ms}^{3.32}\, d_{kpc}^{4.64} \tag{9}$$

Fig. 2 shows a distribution of the 24 millisecond pulsars, with known timing parameters and distance values, on a $p - \dot{p}$ plot. The three full lines show plots of equation (5) for three representative values of E_{max}, namely, 0.3 TeV, 0.5 TeV and 1.0 TeV. Obviously, for pulsars lying along these lines, gamma-rays with maximum energy equal to the corresponding E_{max} values will be able to escape the polar cap region. The three broken lines show plots of the detectability condition (9) for three representative distance values of 0.5 kpc, 1 kpc and 2 kpc. Pulsars located to the left of these lines and with distances smaller than that indicated on the corresponding line, would be potentially detectable with the TACTIC or other similar systems. As seen from Fig. 2, while the 5 pulsars lying to the right of the 0.5 TeV line, are capable of generating curvature gamma-rays with maximum photon energy ≥ 0.5TeV, only two of

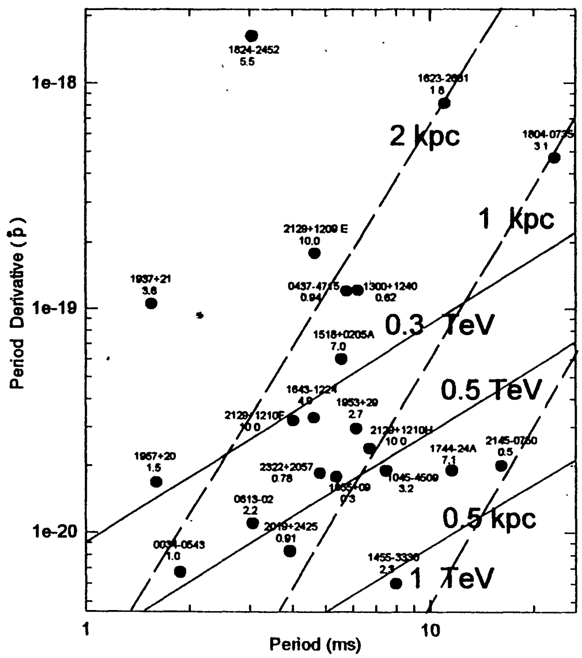

Figure 2. Distribution of 24 ms pulsars on the $p - \dot{p}$ plane. Pulsars lying along the three solid lines are able to emit primary curvature γ-rays or maximum energy equal to that shown on the line. Pulsars lying to the left of three broken lines and located at distances less than that indicated on the line are potentially detectable with TACTIC. The pulsar distances are indicated below the pulsar name.

them (PSRJ 2019+2425 and PSRJ 2145-0750) are capable of producing fluxes above the TACTIC detection threshold as per the Usov model. In addition, PSRB 1855+09, a borderline case, may just be detectable with the TACTIC system especially if the system sensitivity can be improved further by resorting to a periodicity analysis.

4. Conclusions

It has been shown that, while 8 millisecond pulsars are capable of generating ≥ 0.5 TeV gamma-rays fluxes above the TACTIC threshold flux on the basis of energetics, only two millisecond pulsars, namely, PSRJ 2019+2425 and PSRJ 2145–0750, are likely to be detected by this system if the gamma-rays are generated through the Usov model.

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