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The TeV γ-ray visibility of Geminga-like pulsars

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Abstract. It is shown that, while the number of Geminga-like pulsars in the Galaxy may be $\sim 10^3$, the prospects of detecting TeV gamma-ray signals from them are not very encouraging. Arguments are presented to show that Geminga-like pulsars having periods in the range 200–500 ms, surface magnetic fields $> 10^{12}$ Gauss and preferentially located within ~ 2 kpc of the earth may be able to produce detectable TeV gamma-ray signals.

Key words: pulsars: individual: Geminga – pulsars: general – gamma rays: theory

1. Introduction

The brightest till-recently unidentified γ-ray source in the COS-B catalogue (Swanenburg et al. 1981), popularly called 'Geminga' (2CG195+04), has recently been identified as a 237 ms period pulsar in ROSAT soft X-ray data (Halpern and Holt 1992). The identification has been confirmed by the analysis of EGRET data (Bertsch et al. 1992) and the results from the analysis of the archival data from COS-B (Bignami and Caraveo 1992) and SAS-2 (Mattox et al. 1992) experiments. The measurement of pulsations between 1975 and 1992 yields a period derivative of 1.1×10^{-14} ss^{-1}, consistent with that of an isolated pulsar with a characteristic age of $\tau \sim 3.1 \times 10^5$ y (Bignami and Caraveo 1992). From the observed >100 MeV γ-ray flux in the EGRET experiment (Bertsch et al. 1992), the absolute upper limit on its distance is put at < 380 pc (~ 40 pc for a Vela-like efficiency). These conclusions are supported by the observation of a faint optical counterpart, moving at a very high apparent speed of 0.17 arcsec per year, implying a distance of ~ 100 pc (Bignami et al. 1993). The fact that no radio pulsar is identified with Geminga and its peculiar emission characteristics ($L_{\rm x}/L_{\rm opt} \sim 1800$, $L_\gamma/L_{\rm x} \sim 1000$), as compared to other isolated pulsars, like Crab and Vela, suggests that Geminga may be the prototype of a different class of older pulsars which have a comparatively longer pulsation period of a few hundred ms and which are both radio quiet and γ-ray loud.

Several attempts have been made to observe pulsed TeV gamma-ray signals from Geminga, in both the archival and contemporary data following the ROSAT and EGRET discovery of the 237 ms pulsations. Two positive reports have been published by the Durham group (Bowden et al. 1993) and the Tata group (Vishwanath et al. 1993) with pulsed fluxes of 3×10^{-11} cm^{-2} s^{-1} above 1 TeV and 2.1×10^{-11} cm^{-2} s^{-1} above 0.8 TeV respectively. The Whipple group (Akerlof et al. 1993) have, however, reported absence of any evidence for pulsed TeV γ-ray emission from their observations during the period 1989-1991 and quote an upper limit of 6.5×10^{-12} cm^{-2} s^{-1} above 0.5 TeV for the pulsed component. If the pulsed TeV signal is confirmed by future experiments, it would identify Geminga as the prototype of a new class of TeV gamma-ray emitters which lose their rotational kinetic energy mainly via the emission of high energy photons. In view of the fact that Geminga may represent possibly the closest object of this type in the Galaxy, we have attempted to study the visibility of Geminga-like sources at TeV energies in the context of the improved sensitivity of the presently available imaging Cerenkov telescopes. In the present communication, we show that detectable TeV gamma-ray signals can be expected from Geminga-like sources with periods in the range 200–500ms, if they are located within 2 kpc of the earth.

2. Approximate number of Geminga-like pulsars

With only one radio-quiet, gamma-loud pulsar (Geminga) discovered till date, it is not possible to derive a Galactic distribution profile for such sources. A recent study (Mukherjee et al. 1995) of the longitude distribution of the ~ 36 unidentified, low-latitude, EGRET sources has indicated the absence of a strong concentration in longitude within $\sim 30°$ of the Galactic centre, suggesting that these sources are rather uniformly distributed along the Galactic disk. Although the unidentified, low-latitude EGRET sources appear to be different from Geminga-like pulsars (Mukherjee et al. 1995), we can start with the assumption that there are N Geminga-like sources distributed uniformly throughout the Galactic disk of radius $R_{\rm g}$ (~ 10 kpc) and thickness $H_{\rm g}$ (~ 200 pc). The distance of the closest such pulsar from the earth is then given by,

$$D \sim \left(\frac{\bar{\Lambda} R_{\rm g}^2 H_{\rm g}}{N}\right)^{1/3}. \tag{1}$$

If we further assume that Geminga represents the closest example of a pulsar belonging to this population, we have

$$N = \bar{\Lambda} R_g^2 H_g / D_g^3 \quad (2)$$

where D_g is the inferred distance to Geminga. Putting in the appropriate values of R_g and H_g, we get

$$N \sim 6.3 \times 10^4 \; for \; D_g = 100\,\mathrm{pc}$$

where we have used a value of 100 pc for the most probable distance to Geminga (Bignami and Caraveo 1992). This value of N is too large to be acceptable as it implies a birth rate of $\sim$ 1 per 10 years (for a typical pulsar life-time of $\sim 5 \times 10^5$ y), in sharp contrast with a value of 1 per 30–100 years generally quoted in literature for the radio pulsar birth rate. Moreover, the inferred value of N, in the actual conditions, represents only a lower limit on the number of these sources, since the assumption of a uniform density right through the Galactic plane may not be strictly valid if these sources (pulsars) are the end products of massive stars, as in the case of radio pulsars. The assumption of a uniform distribution, therefore, does not seem to be valid for Geminga-like pulsars.

The radio pulsar population distribution in the Galaxy has been well-studied (Taylor et al. 1993) and, with only one gamma-loud pulsar detected so far, there is no compelling reason to believe that Geminga-like pulsars come from a different parent population. To arrive at a more reasonable limit on their number, we assume that Geminga-like pulsars are born from massive stars ($\log M/M_\odot > 0.5$), with a birth rate per unit volume varying exponentially with distance (R) from the Galactic centre as $\sim e^{-R/R_0}$ (R_0 = 4.5 kpc) and with distance (z) from the Galactic plane as $\sim e^{-z/z_0}$ (z_0 = 100 pc) as has been considered in case of old pulsars by Paczynski (1990). If the thin disk capable of producing Geminga-like pulsars is considered to extend from $R = 0$ to $R = 10$ kpc and $z = 0$ to $z = \pm 100$ pc, we can write the probability distributions at the Sun's position as

$$P(Z')dZ' = \frac{1}{Z_0} e^{-(Z'+Z_s)/Z_0} dz' \quad (3)$$

$$\text{and } P(R')dR' = K \cdot \frac{(R'+R_s)}{R_0^2} e^{-(R'+R_s)/R_0} dR' \quad (4)$$

where the primes indicate that the distances are measured with respect to the Sun's position, R_s (= 8.5 kpc) and Z_s (= 0) represent the distance of Sun from the Galactic centre and from the Galactic plane respectively and K (≈ 1) is a normalization constant. If there are N Geminga-like pulsars in the Galaxy, and only one such pulsar is found in the volume element bounded by $z' = 0$ and $z' = Z_g$ and $R' = 0$ to $R' = R_g$ (R_g and Z_g being the distance of Geminga from Sun and its distance above the Galactic plane respectively), then

$$N \int_0^{R_g} \int_0^{Z_g} \frac{K}{Z_0} \frac{(R'+R_s)}{R_0^2} e^{-(R'+R_s)/R_0} e^{-(Z'+Z_s)/Z_0} dz' dR' = 1 \quad (5)$$

Integration of (5) with R_g = 100 pc and Z_g = 10 pc gives,

$$N \approx 1660\,. \quad (6)$$

We, therefore, find that, while Geminga-like pulsars form a small percentage ($\sim 0.5\%$) of the total radio pulsar population ($\sim 3 \times 10^5$) in the Galaxy, their number is quite large in absolute terms. It is, thus, surprising that not many of them have been detected at ≥ 100 MeV in the satellite experiments conducted so far. Even if we assume that most of the unidentified ≥ 100 MeV sources detected in the SAS-2, COS-B and EGRET experiments are Geminga-like in characteristics, the total number detected so far would not exceed 100. One possible explanation of this discrepancy could be in terms of the self-absorption of high energy gamma-rays from these sources through photon-photon interactions with the background X-ray photon field in the source neighbourhood or enroute in case of more distant sources. A more likely explanation of this discrepancy would be in terms of the intrinsically smaller luminosities (spin-down energy loss) of these sources which renders only the closest ones detectable at the sensitivity levels available with the present satellite experiments. Alternatively, a small γ-ray beam width could also result in fewer detections at ≥ 100 MeV energy, due to the less likely interception of the gamma-ray beam by the detector.

The EGRET experiment on CGRO has a threshold for detection of $\sim 2 \times 10^{-10}$ erg cm^{-2} s^{-1} at ≥ 100 MeV energy for sources in the Galactic plane. This translates to a source threshold luminosity of

$$L_{\mathrm{thresh}} \sim 1.82 \times 10^{33} d_{\mathrm{kpc}}^2 \Delta\Omega \,\mathrm{erg\,s^{-1}} \quad (7)$$

for emission beamed within a solid angle of $\Delta\Omega$ steradian. If all the spin-down energy of a Geminga-like source is converted to ≥ 100 MeV gamma-rays, we can set a limit on the maximum distance upto which such a source will be detected by EGRET. The limit is given by

$$d_{\mathrm{kpc}} \leq \left(\frac{8\bar{\Lambda}^2}{5} \frac{MR^2\dot{P}}{\Delta\Omega P^3} \cdot \frac{1}{1.82 \times 10^{33}} \right)^{0.5} . \quad (8)$$

For a source with $M = 1.4 M_\odot$ ($M_\odot \sim 2 \times 10^{33}$ g), $R = 10^6$ cm, P = 200 ms and $\dot{P} = 10^{-14}$, we find that

$$d_{\mathrm{max}} \leq 5.51/(\Delta\Omega)^{0.5}\,\mathrm{kpc}\,. \quad (9)$$

Thus, only the closest such pulsars will be detectable with EGRET ($d_{\mathrm{max}} \leq 1.55$ kpc for isotropic emission and 100% gamma-ray conversion efficiency) unless the gamma-ray emission is confined to a much narrower beam (<1 steradian). Moreover, the limiting distance will be further lowered if only a small fraction of the available spin-down energy is converted to ≥ 100 MeV gamma-rays.

3. Detectability of Geminga-like pulsars at TeV energies

The probability that a given Geminga-like pulsar will be detected as a TeV source depends both on the energy flux in the

TeV range received on the earth and the threshold energy flux of the detection system. The former is determined by the total spin-down energy loss rate of the pulsar, the conversion efficiency η from spin-down power to TeV gamma-rays and the distance to the pulsar. TeV gamma-ray emission from pulsars with strong magnetic fields is generally explained in terms of the outer gap models (Cheng, Ho and Ruderman 1986; Ruderman & Cheng 1988; Chen & Ruderman, 1993). Cheng and De Jager (1990) have simplified the outer gap model qualitatively by distinguishing between two classes of pulsars, namely, Vela-like and post Vela-like (relatively older) pulsars, on the basis of a parameter which represents the efficiency with which a pulsar can maintain a self-sustaining outer gap. Geminga is believed to belong to the category of post Vela-like pulsars in which the conversion efficiency of spin-down power to TeV gamma-ray luminosity increases to a value of ~ 0.5 as compared to a value of $\sim 10^{-4}$ for Vela-like pulsars. However, recent observations on 11 post Vela-like pulsars with the Nooitgedacht telescope (Nel et al. 1992) have indicated that $\eta \ll 1$ for post Vela-like pulsars as against the expected value of ~ 0.5. In the follwing discussion, we have adopted a more realistic value of $\eta = 0.1$ for the Geminga-like pulsars in order to investigate their detectability at TeV energies.

Assuming that the ultimate source of TeV luminosity from Geminga-like sources is the spin-down power of the slowing-down pulsar, $\dot{E}$, we can write

$$L_\gamma = \dot{E} = \frac{8\bar{\Lambda}^2}{5} M R^2 \dot{P} P^{-3} \eta \, \mathrm{erg\,s^{-1}} \quad (10)$$

where M, R, P and $\dot{P}$ represent the mass, radius, period and period derivative of the pulsar (neutron star) and η is the conversion efficiency for spin-down power to TeV γ-ray luminosity. If $|E_\gamma|$ is the mean energy of the isotropically emitted TeV gamma-rays, the flux at earth is,

$$F_\gamma = \frac{8\bar{\Lambda}^2 \eta}{5} M R^2 \dot{P}/P^3 \cdot 4\bar{\Lambda} d^2 |E_\gamma| \quad (11)$$

where d(cm) is the distance to the source. Here we assume that the TeV gamma-rays are emitted far from the pulsar surface so that they escape absorption due to $\gamma \rightarrow e^+ + e^-$ pair production process in the pulsar's magnetic field. Using standard values for M ($\sim 1.4 M_\odot$, $M_\odot$ = solar mass) and R (=10^6 cm), Eq. 11 can be written as

$$F_\gamma = \frac{2.29 \times 10^{-4} \eta \dot{P}_{-15}}{P^3_{(\mathrm{ms})} d^2_{(\mathrm{kpc})} E_\gamma(\mathrm{TeV})} \mathrm{photons\,cm^{-2}\,s^{-1}} \quad (12)$$

where $\dot{P}_{-15} = \dot{P}/10^{-15}$.

If the pulsars are to be detectable at a level of 1 Crab Nebula flux unit, i. e., 7×10^{-11} photons cm^{-2} s^{-1} above $E_\gamma = 0.4$ TeV (Vacanti et al. 1991), we can write Eq. (12) above as the inequality,

$$\frac{2.29 \times 10^{-4} \dot{P}_{-15} \eta}{P^3_{\mathrm{ms}} d^2_{(\mathrm{kpc})}} \geq 7 \times 10^{-11} \text{ for } |E_\gamma| = 1\,\mathrm{TeV} \quad (13)$$

Equation 13 can be put in the form,

$$P^3_{\mathrm{ms}} d^2_{(\mathrm{kpc})} \leq 3.27 \times 10^6 \dot{P}_{-15} \eta \quad (14)$$

The inequality (14) can also be expressed in terms of the surface magnetic field strength B_s (Gauss). Equating the rotational energy loss rate from the pulsar to the energy loss rate due to magnetic dipole radiation, we obtain (Harding 1981),

$$B_\mathrm{s} = 10^{15} (I/R^6)^{1/2} (P\dot{P})^{1/2} \,\mathrm{Gauss} \quad (15)$$

which can be rewritten as (for $R = 10^6$ cm),

$$B_\mathrm{s}(\mathrm{Gauss}) \approx 3.35 \times 10^{10} P^{1/2}_{\mathrm{ms}} \dot{P}^{1/2}_{-15} \quad (16)$$

Eliminating $\dot{P}_{-15}$ from 14 and 16, we get

$$B_\mathrm{s} \geq 1.85 \times 10^7 P^2_{\mathrm{ms}} d_{\mathrm{kpc}} \eta^{-0.5} \quad (17)$$

Figure 1 shows a plot of the inequality (17) for two representative values of the gamma-ray conversion efficiency η, namely $\eta = 0.1$ (for Geminga-like pulsars) and, $\eta = 10^{-4}$ (for Vela-like pulsars). Clearly, the region to the left of each solid line represents the allowed zone of P_ms and B_s values for Geminga-like pulsars located at typical distances of 0.5 kpc and 5 kpc respectively, which can be detected as TeV gamma-ray emitters at a flux value of 1 Crab Nebula flux unit. Similarly, the region to the left of the two broken lines represents the allowed B_s-P_ms zone for the detection of Vela-like pulsars at representative distances of 1 kpc and 10 kpc respectively. Taking $B_\mathrm{s} = 10^{13}$ G as the upper limit on the intensity of the magnetic field at the pulsar surface (Taylor et al. 1993), we find that Geminga-like pulsars, lying within 0.5 kpc of the earth, can be detected as TeV emitters only if they have periods ≤ 400 ms, while those lying at distances ≥ 5 kpc can be detected only if their periods are ≤ 100 ms. Further, the chances of detecting TeV emission from such sources are small for periods ≥ 400 ms as it would demand unexpectedly high ($> 10^{13}$ G) surface magnetic field strengths or, in other words, very large values of the period derivative ($\dot{P} > 10^{-12}$). If we put a lower limit of 200 ms on the period of old, Geminga-like pulsars, then such pulsars can be detected as TeV emitters only if they lie within ~ 2 kpc of the earth. The approximate number of Geminga-like pulsars within 2 kpc of the earth can be estimated from Eq. 5 to be ~ 120. Even if only 10% of these pulsars have periods in the range 200 ms–400 ms, then about 10 Geminga-like pulsars may, at least, be awaiting detection at TeV energies with the available detection systems. In the case of Vela-like pulsars, on the other hand, TeV gamma-ray detection is found to be possible only for sources with periods ≤ 40 ms, lying between 1 kpc and 10 kpc of the earth.

In Fig. 1, we have also plotted, in B_s-P_ms space, the location of several known pulsars which have been the subject of various searches conducted for detecting possible TeV gamma-ray emission, including that of Nel et al. (1992). While no pulsar shows up as a definite candidate for detection at TeV energies, the most likely candidates for TeV gamma-ray detection, under favourable conditions, may be the Crab pulsar among the

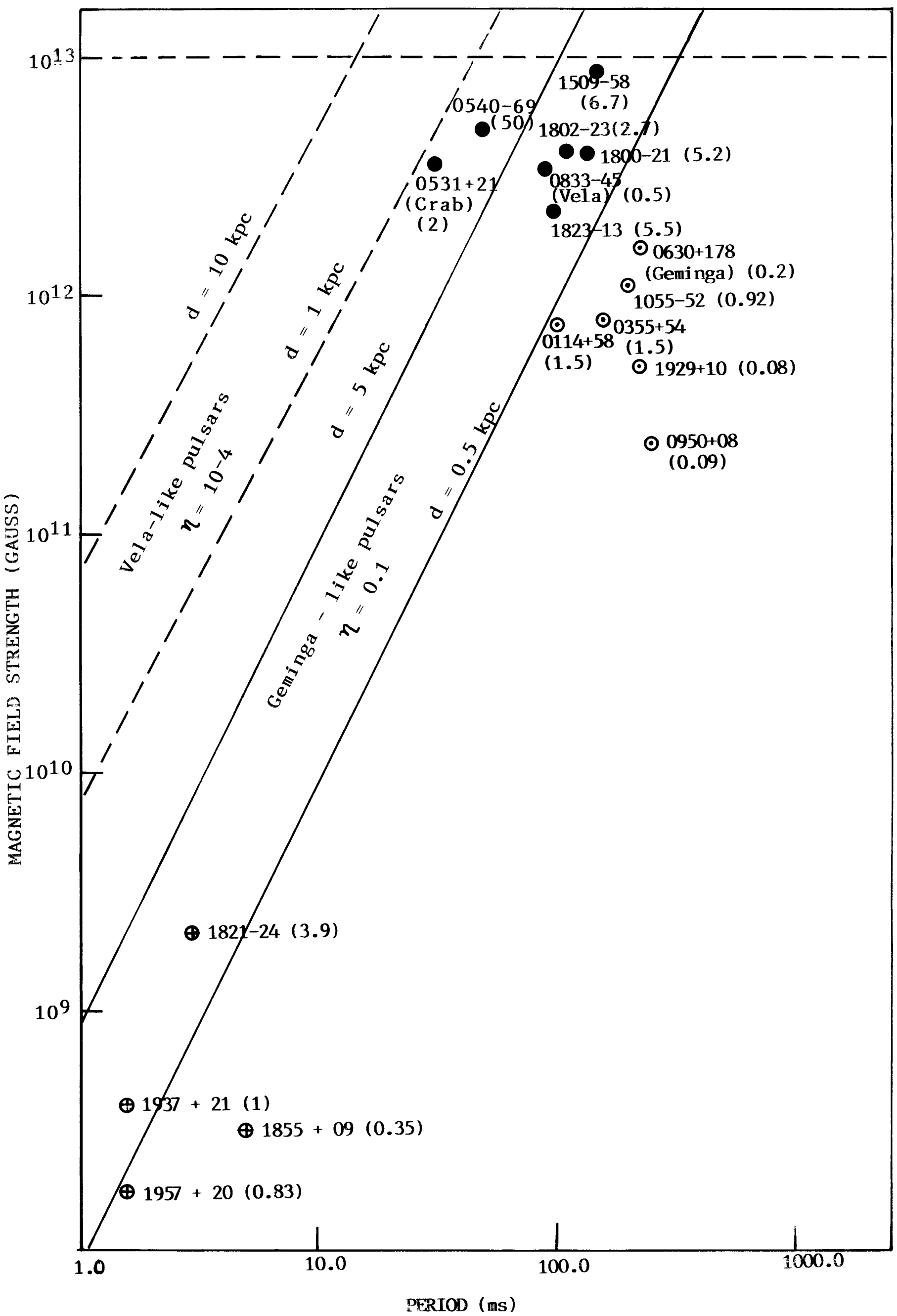

Fig. 1. Surface magnetic field strength, as a function of pulsar period, required for a pulsar to be detectable at a flux level of 7×10^{-11} photons cm^{-2} s^{-1} above 1 TeV at typical distances of 0.5 kpc and 5 kpc in case of Geminga-like pulsars (full lines) and at typical distances of 1 kpc and 10 kpc for young Vela-like pulsars (broken lines). The TeV gamma-ray conversion efficiency has been assumed to be 0.1 for the Geminga-like pulsars and 10^{-4} for the Vela-like pulsars. The positions of several pulsars in the B_s-P_{ms} space, investigated for TeV gamma-ray emission are also shown, the distance to the pulsar being given in parenthesis under / besides the pulsar name. Filled circles (•) represent young Vela-like pulsars, $\odot$ represents older ($> 10^5$ y) Geminga-like pulsars while $\oplus$ represents binary pulsars. For other details, kindly refer to the text

young pulsars and PSR 1055-52, PSR 0114+58, PSR 0355+54 and Geminga among the older pulsars. No Vela-like pulsar, including the Vela pulsar itself, is found to be detectable at TeV energies in the present model. This conclusion is in agreement with the results obtained by Nel et al. (1992) who have failed to detect TeV gamma-ray emission from a majority of pulsars observed by them, including the Vela pulsar and PSR 1706-44. The reported detection of a positive TeV signal from PSR 1509-58 over a 3-year period, reported by them, cannot be explained by the present model. More observational support is needed to confirm PSR 1509-58 as a TeV gamma-ray emitter. Most of the other pulsars shown in Fig. 1, including the binary millisecond pulsars, cannot produce detectable TeV signals unless their conversion efficiencies are much larger than that of the Vela-like pulsars. The survey by Nel et al. (1992) has also failed to detect TeV gamma-ray emission from them, in agreement with the above conclusion.

4. Conclusion

We have estimated the approximate number of radio-quiet, gamma-loud pulsars, similar in characteristics to the prototype source Geminga, to be $\sim$ 1600 in the Galaxy on the assumption that Geminga is the closest source of this class. On the basis of system energetics and a reasonable value of $\eta \sim 0.1$ for the spin-down energy loss to TeV gamma-ray luminosity conversion efficiency, we estimate that ~ 10 such sources, with periods in the range 200–500 ms and located within 2 kpc of the earth, may be detectable at TeV energies at a flux level equal to that at which Crab Nebula has been detected by the Whipple system above 0.4 TeV energies. In case the TeV gamma-ray conversion efficiency is higher than the assumed value of $\eta = 0.1$, as predicted, for example, by the outer gap models, or if the TeV γ-rays are emitted in a narrow beam, this class of sources may represent an important, new population of hitherto unknown TeV gamma-ray emitters.

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