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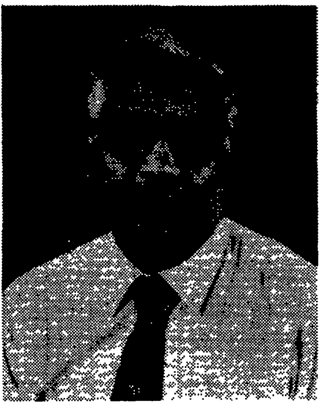

High energy gamma-ray pulsars

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Abstract. To date we know the existence of six high energy gamma-ray (HEGR) pulsars and a possible seventh candidate, besides a solitary low energy gamma-ray pulsar. In this paper, we briefly summarize the observations on the seven HEGR pulsars. We will then examine, treating all the HEGR pulsars as a 'population', if there is any emerging trend in their properties and try to compare the results with theoretical predictions.

Key words : pulsars, gamma-rays, high-energy

1. Introduction

It has long been established that pulsars are highly magnetized rotating neutron stars left behind in the aftermath of supernova explosions of massive stars. Nearly all of them have been discovered by radio observations, with the first discovery having been made by Hewish *et al.*, (1968). To date nearly 600 radio pulsars have been detected; see Taylor *et al.*, (1993) for a catalogue listing their important properties. Basically the radio observations on a pulsar yield the intensity, shape of the light curve, period (P), time derivative of the period ($\dot{P}$), source coordinates and the dispersion measure. Using these data in conjunction with plausible models, one derives the distance, surface magnetic field and characteristic age of a pulsar. Pulsar magnetospheres are too complex to enable one to develop accurate models for the emission of electromagnetic radiation. Attempts to develop emission models for pulsars have been a continuing effort ever since their discovery. In this context, a knowledge of emissions at different energy ranges (besides the radio energy range) is of great help to theorists. Several groups tried to detect pulsed emission by the known radio pulsars at optical, x-ray and gamma-ray wavelengths but succeeded only in a small percentage of cases; see the reviews by Manchester and Taylor (1977) and Lyne and Graham-Smith (1990).

In this paper we will review the observed properties of high energy gamma-ray (HEGR) pulsars; here we define a HEGR pulsar as one emitting pulsed gamma-rays in the energy range 30 MeV - 30 GeV, which is essentially the range of sensitivity of the EGRET detector

(Kanbach, 1989 and Thompson *et al.*, 1993) aboard the Compton Gamma Ray Observatory (CGRO) launched in April 1991. To date the existence of six HEGR pulsars is well established; in addition there is a possible seventh candidate. These are the Vela (PSR B0833 - 45), Crab (PSR B0531+21). Geminga (PSR J0633 + 1746), PSR B1055-52, PSR B1706-44, PSR B1951+32 and PSR B0656+14. It should be mentioned here that there is another gamma-ray pulsar, PSR B1509-58, that has been detected only at low energies, 60 keV and 2 MeV, by the other detectors on the CGRO by BATSE (Wilson *et al.*, 1993)), OSSE (Ulmer *et al.*, 1993) and COMPTEL (Bennett *et al.*, 1993) but not by EGRET. Of the seven HEGR pulsars listed above, the first two (viz. the Vela and Crab pulsars) were seen by other groups even before the launch of CGRO. The remaining five pulsars, were discovered using the data from the EGRET detector aboard the CGRO. This is largely due to the higher sensitivity, lower background and better angular resolution (Thompson *et al.*, 1993) of the EGRET detector in comparison with the two earlier satellite-borne detectors, SAS-2 and COS-B.

Attention must be drawn here to an important difference between the pulsar discovery processes at radio and gamma-ray wavelengths. Whereas the radio data can be analysed all by itself to discover a pulsar, such is not the case with the HEGR observations. Reasons are (i) the pulsar-generated HEGR are submerged in the vast background (one or two orders of magnitude higher) of HEGR generated by cosmic ray interactions with interstellar matter and (ii) the pulsar-generated HEGR fluxes are very low e.g. EGRET receives only one HEGR from the Crab pulsar in approximately 10,000 rotations of the pulsar. Because of these two reasons it is not possible to carry out a parametric search using the HEGR data in the P-$\dot{P}$ space to make any statistically meaningful statement. One must have input information on P and $\dot{P}$ (atleast, very approximately) gleaned from radio or X-ray observations to limit the number of trial searches. In the hindsight, one could have analysed the EGRET data on Geminga without any input on pulsar elements from observations at other wavelengths to discover the pulsed nature of HEGR. The EGRET group has indeed proved the veracity of this statement by actually carrying out the analysis. Geminga is an exception because it is a very bright HEGR source, its possible location is strongly and accurately hinted at by the X-ray and optical observations and the search range in the P - $\dot{P}$ plane is reasonably limited.

In the next section we will outline a few of the important features of pulsed HEGR emission by each of the pulsars. In Section 3 we will discuss these results treating all the HEGR pulsars as a 'population' to see if there are any emerging trends and try to compare the results with theoretical predictions. Finally we end the paper with comments on future prospects in the field.

2. Individual high energy gamma-ray pulsars

As we have to be necessarily brief, we will be giving only a few of the findings referring the reader to the publications on each of the HEGR pulsars for details. We have also given in Tables 1, 2 and 3 some of the observed and inferred parameters on each HEGR pulsar.

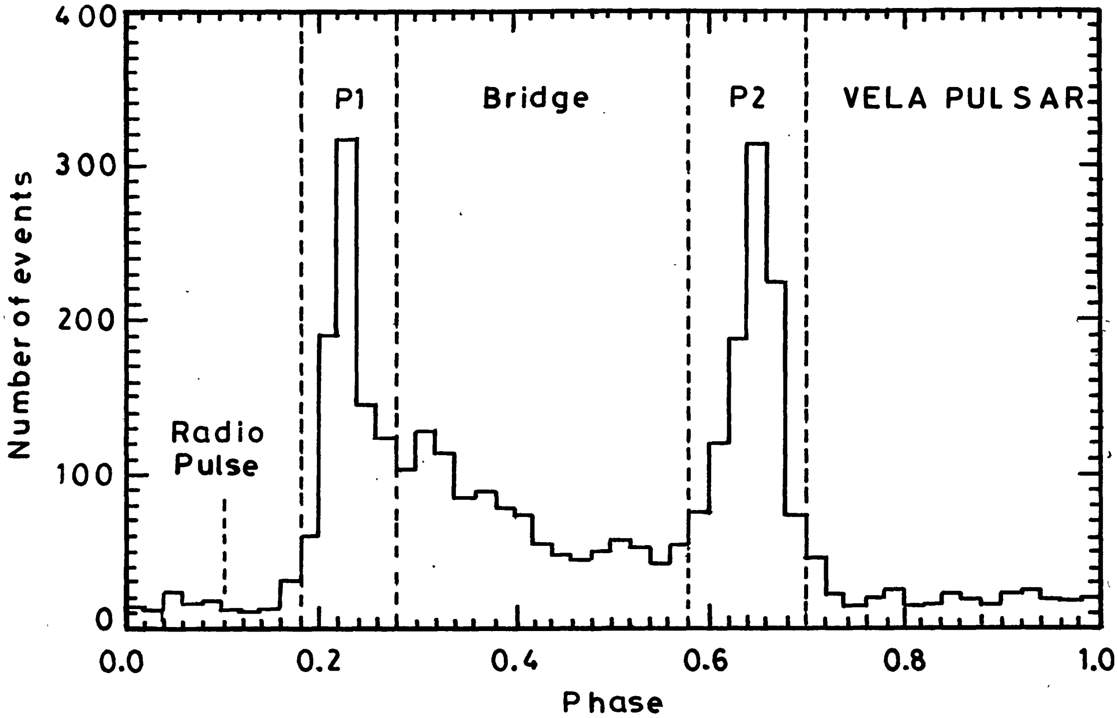

Figure 1. Light curve of the Vela pulsar at energies > 100 MeV from the viewing period VP0080. The position of the radio pulse peak in phase is shown by the short dashed line and the boundaries of phase regions of the two gamma-ray peaks and the bridge are shown by the dashed lines.

(a) The Vela pulsar (PSR B0833-45)

Vela is the brightest HEGR pulsar at energies E > 100 MeV. Though seen by the earlier SAS-2 and COS-B satellites, observations by EGRET are statistically more significant. The large statistics of EGRET data over the first 1.5 years of its operation allowed Kanbach *et al.*, (1994) to obtain phase-resolved energy spectra, to determine the locations and widths of the two peaks and to set upper limits to any unpulsed emission. The HEGR light curve determined from a two week observation by EGRET is shown in Figure 1. The pulsed HEGR emission appears mainly in two peaks and to a lesser extent in the bridge region in between the two peaks. The two peaks are separated by 0.424 ± 0.002 in phase with the first HEGR peak lagging the radio peak by 0.118 ± 0.001 in phase. The total spectrum can be described by a power law with a spectral index of –1.70 ± 0.02 in the range 30 MeV to 2 GeV. The spectrum steepens somewhere between 2 and 4 GeV. The phase-resolved spectra exhibit phase-dependent indices in the range –1.5 to –2.2; the spectra of HEGR emitted in the bridge region are harder than those at other phases. The average total intensity of HEGR at E > 100 MeV is (7.8 ± 1.0) 10^{-6} photons/cm^2/sec.

Table 1. Observed parameters of the gamma ray pulsars.

Pulsar	l deg.	b deg.	P(s)	$\dot{P}$ (10^{-15} s/s)	spectral index	F* (erg $cm^{-2}s^{-1}$)
Crab	184.6	-5.8	0.033	421	2.15	1.0E-9
Geminga	195.1	4.3	0.237	11.0	1.50	3.7E-9
Vela	263.6	-2.8	0.089	125	1.70	7.1E-9
B1055-52	286.0	6.6	0.197	5.83	1.18	4.2E-10
B1706-44	343.1	-2.7	0.102	93	1.72	8.3E-10
B1951+32	68.8	2.8	0.040	5.85	1.74	2.4E-10
B0656+14	201.1	8.3	0.385	55.0	2.8	9E-12

*observed gamma ray energy flux at E > 100 MeV.

Table 2. Inferred parameters of the gamma ray pulsars.

Pulsar	Dist.(kpc)	Age(yr)	B(G)	$\dot{E}$ (erg s^{-1})	L*# (erg s^{-1})	efficiency* @
Crab	2.0	1.3E3	3.8E12	4.5E38	3.9E34	0.00009
Geminga	0.25	3.4E5	1.6E12	3.3E34	2.2E33	0.068
Vela	0.50	1.1E4	3.4E12	7.0E36	1.7E34	0.0024
B1055-52	1.5	5.3E5	1.1E12	3.0E34	9.3E33	0.31
B1706-44	1.8	1.7E4	3.1E12	3.4E36	2.6E34	0.0077
B1951+32	2.5	1.1E5	4.9E11	3.7E36	1.4E34	0.004
B0656+14	0.76	1.1E5	4.7E12	3.8E34	4.7E31	0.001

*Proportional to the beaming factor # high energy gamma ray luminosity
@ conversion efficiency of spin-down energy loss into gamma ray energy

Ramanamurthy *et al.*, (1995a) utilised an extended EGRET database collected over 3 years to study the variability of the shape of the light curve, intensity and spectral index with time. These authors concluded that the shape of the light curve is generally stable except for an occasional variation in the ratio of counts under the two peaks at energies > 2000 MeV. While the integral fluxes at E > 100 MeV are only mildly variable (± 12% with respect to the average and within 2 standard deviations), the variation in the spectral index, from –1.63 to –2.00, appears more significant, between 2 and 3 sigma. The conversion efficiency of spin-down energy loss of pulsar into pulsed HEGR is approximately 0.0024, though this figure depends on the assumptions made on the beaming factor and errors in the distance to the pulsars; see Thompson *et al.*, (1994) for an elaboration on this point.

Table 3. Additional observed parameters of the gamma ray pulsars

Pulsar	No.of peaks	Peak* separation	Position* of 1st peak w.r.t. radio	Spectral index	Pulsed** flux
Vela	2	0.42	0.12	1.70	7.8
Geminga	2	0.50	no radio	1.50	3.5
Crab	2	0.40	0.00	2.15	1.7
B1706-44	2(3?)	0.18	0.27	1.27, 2.25@	1.3
B1055-52	1#	—	? 1.18	0.24	
B1951+32	2	0.44	0.16	1.74	0.16
B0656+14	1##	—	0.26	2.80	0.04

* in units of phase

** time-averaged flux in units of 10**–6cm**–2s**–1 at E > 100 MeV

@ spectral break at E = 1 GeV (Thompson *et al.*, 1996)

width = 0.35 phase

width = 0.12 phase

(b) The Geminga pulsar (PSR J0623 + 1746)

Geminga is the second brightest pulsed HEGR source in the sky. The intergral flux at E > 100 MeV is 3.5 10^{-6} photons/cm^2/sec. The HEGR data on this source from the earlier detectors failed to see the pulsed nature of HEGR because there was no input on pulsar elements available either from X-ray or from radio observations. It is not seen to date to pulsate in radio. Once the ROSAT X-ray data yielded (Halpern and Holt, 1992) the value of the period, P, Bertsch *et al.*, (1992) quickly analysed the EGRET data by carrying out a parametric search over a limited range of P around the value given by Halpern and Holt and established the pulsed nature of the HEGR emission besides deriving a value for $\dot{P}$. There is a point of etymological interest here. Prior to the discovery that Geminga is a pulsar, a pulsar has been defined as a pulsating radio source. With the arrival of the apparently radio-quiet Geminga on the scene, one has to re-define a pulsar as an object that emits pulsed electromagnetic radiation regardless of whether it pulsates in radio or not.

Referring the reader to Bertsch *et al.*, (1992), Mayer-Hasselwander *et al.*, (1994) and Ramanamurthy *et al.*, (1995a) for the details, we will only briefly outline here some important findings. Like in the case of the Vela and Crab pulsars, the HEGR emission appears in two peaks and in the region (bridge) in between the two peaks. In this case the two peaks are separated by 0.5 in phase. There appears to be no unpulsed emission of HEGR. The energy spectrum in the range 30 MeV to 2 GeV over all the phases is compatible with a power law with a spectral index of –1.50 ± 0.08. The spectrum steepens at energies > 2 GeV. Phase-resolved spectra show power laws with significant phase-dependent variation, in the range –1.22 to –1.67, of the spectral index; in particular the spectrum of HEGR photons in the second peak is harder than those at the other phases. The shapes of light curves do not vary with time over a 3 year time span. However, there is an indication of mild variability (± 16%, i.e. within ± 2 sigma) in the total flux at $E > 100$ MeV and of slightly more significant variability in the spectral index (~ 3 sigma) in the range of –1.2 to –1.7. Efficiency of conversion of spin-down energy loss into HEGR appears to be 0.068 in this case; see Thompson *et al.*, (1994).

(c) The Crab pulsar (PSR B0531 + 21)

We will give a few important results here referring to Nolan *et al.*, (1993) and Ramanamurthy *et al.*, (1995a) for the details.

The Crab pulsar is the third brightest HEGR pulsar with a phase-averaged pulsed flux of $1.74\ 10^{-6}$ photons/cm^2/sec at $E > 100$ MeV. Unlike in the case of the Vela and the Geminga pulsars, there is a measurable unpulsed flux of $0.7\ 10^{-6}$ photons/cm^2/sec at $E > 100$ MeV, which is emitted most probably by the nebula surrounding the pulsar (despite its better angular resolution, the EGRET detector cannot resolve the Crab pulsar from the Crab nebula). The ratio of the unpulsed to the total emission from the Crab as a whole varies with energy starting from a value of ~0.6 at E ~40 MeV, reaching a minimum of 0.2 at E ~1000 MeV and again going up to $\gtrsim 0.8$ at $E > 10$ GeV.

The HEGR light curve of the Crab pulsar, like those of the Vela and Geminga pulsars, exhibits two peaks with finite emission from the bridge region as well. The intra-peak separation is (0.40 ± 0.02) in phase. The two peaks nearly coincide with the two radio peaks. It is often stated that in the case of Crab pulsar, the positions of the two peaks align perfectly well all the way from the radio to gamma-ray energies. However, if one takes a closer look at the more recent data (especially at optical wavelengths), there does seem to be a monotonic decrease of the phase separation with energy, from 0.45 to 0.39; see Ramanamurthy (1994) for the details.

The energy spectrum of the total pulsed emission from the Crab pulsar is compatible with a power law with a spectral index of –2.15 ± 0.04 in the range of 50 MeV – 10 GeV. The spectral index of the phase-resolved energy spectra is phase dependent in the range –1.4 to –2.2 with the spectra being hardest in the phase region corresponding to the bridge. The integral flux from the Crab pulsar at $E > 100$ MeV appears to be constant in time over a 3 year period. There is a hint for variability in the spectral index of the total spectrum in the range –1.95 to –2.7, but within 2 standard deviations.

The HEGR light curve appears to be constant in time except for a statistically significant variability in the ratio, P2/P1, of the background-subtracted counts under the two peaks. Earlier the COS-B group (Özel & Mayer-Hasselwander, 1984; Kanbach, 1990 and Ozel 1991), examining the SAS-2 and COS-B data, have noted that the P2/P1 ratio varies sinusoidally with a period of ~14 years, and this is attributed to nutation of the neutron star. Ramanamurthy *et al.*, (1995a) have included the EGRET data and re-analysed the time variability over a span of 24 years. The expression for the best sinusoidal fit is given by

$$P2/P1 = 0.91 - 0.5 \sin (2\pi (T - 2653) / 4907)$$

where T = JD – 2440000 is the epoch of observation. The result is shown in figure 2. The reduced χ^2 for the sinusoidal and null hypothesis fits are respectively 1.29 and 1.81, resulting in probabilities of 0.20 and 0.03. While the sinusoidal fit is slightly better, the null hypothesis cannot be ruled out at the moment.

The conversion efficiency of the spin-down energy-loss into HEGR is 0.00009.

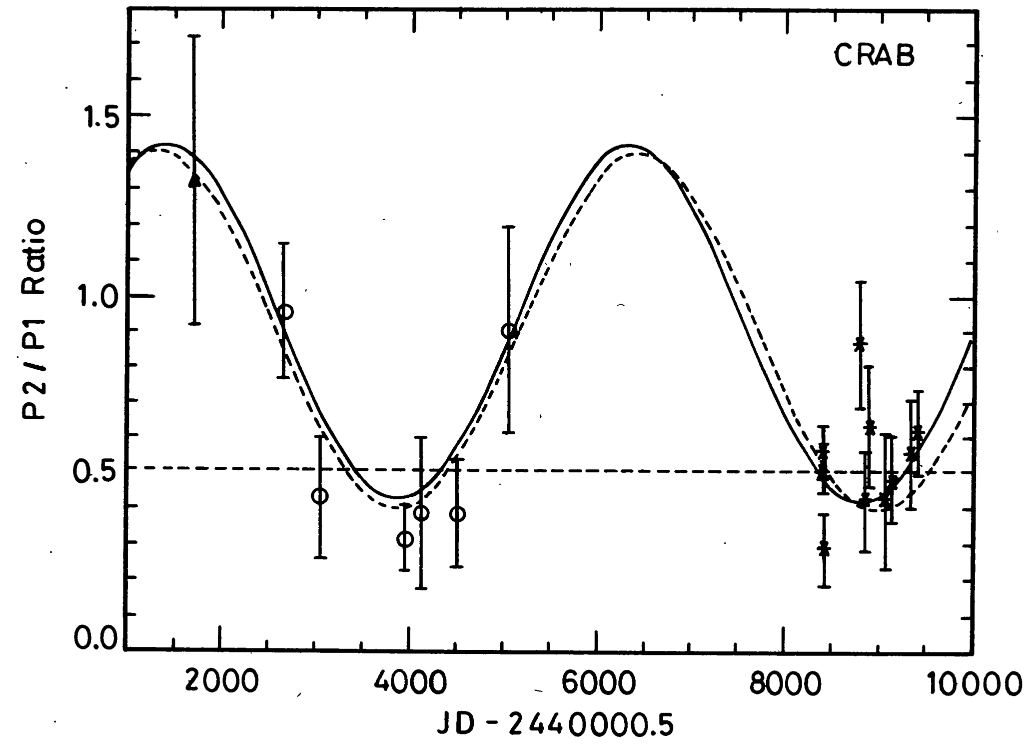

Figure 2. Ration of high energy gamma-ray emission under the second peak to that under the first peak of the Crab pulsar light curve for E > 50 MeV is shown as function of time (Julian Days) from SAS-2 (triangle), COS-B (circles) and EGRET (asterisks) observations. The dotted and solid lines are respectively an earlier and the latest sinusoidal best fits while the dashed straight line is the fit for null (i.e. no variation) hypothesis.

(d) PSR B1706-44

The discovery that the object is an HEGR pulsar has been reported by Thompson *et al.*, (1992) and an updated more recent analysis, by Thompson *et al.*, (1996). The pulsed flux is (1.28 ± 0.08) 10^{-6} photons/cm^2/sec and the 95% C.L. upper limit to the unpulsed flux is 0.24 10^{-6} photons/cm^2/sec both at E > 100 MeV. The statistics of the pulsar related HEGR are too small (~1000 photons at E > 100 MeV over 4 years of observations) to enable one to carry out phase-resolved energy spectroscopy. The phase-averaged photon number energy spectrum shows a break at E 1000 MeV. The power law spectrum has indices of –1.27 ± 0.09 at E < 1000 MeV and –2.25 ± 0.13 at E > 1000 MeV. The conversion efficiency of the spin-down energy loss into HEGR is 0.01.

The HEGR light curve shows activity in the phase region 0.24 to 0.52 (radio phase = 0.00). The light curve appears to consist of either 3 peaks (probability = 0.48) or 2 peaks (probability = 0.32). It is not consistent with a single peak (probability = 0.007). In the case of a 2-peak fit, the peaks appear at the phases 0.27 ± 0.02 and 0.45 ± 0.02, making the intra-peak separation ~ 0.18.

There is no evidence for long term variability of gamma-ray flux within the rather large statistical errors ~ ± 25%. The observable power output by the pulsar is dominated by the gammarray emission.

(e) PSR B1055-52

Discovery of this HEGR pulsar was announced by Fierro *et al.*, (1993). It is seen as an HEGR pulsar at energies > 300 MeV. Below 300 MeV, the signal becomes hard to distinguish above the diffuse Galactic radiation. The HEGR light curve exhibits a single broad ($\Delta\phi = 0.35$) peak, most of the pulsed emission preceding the radio peak in phase. The phase-averaged pulsed HEGR flux is (2.4 ± 0.4) 10^{-7} photons/cm^2/sec at E > 100 MeV.

The efficiency for conversion of spin-down energy loss into HEGR is calculated to be 0.31. This pulsar has the highest conversion efficiency and the hardest spectrum among all the HEGR pulsars. Low photon statistics did not allow phase-resolved spectroscopy.

(f) PSR B1951+32

The discovery paper of this HEGR pulsar is published by Ramanamurthy *et al.*, (1995b). The HEGR light curve exhibits two peaks at the phases 0.16 and 0.60 (radio peak at the phase 0.00). The intra-peak separation, 0.44 in phase, is comparable to those in the case of the Vela, Crab and Geminga pulsars.

The phase-averaged pulsed flux is (1.6 ± 0.2) 10^{-7} photons/cm^2/sec at E > 100 MeV with no evidence for unpulsed emission. The energy spectrum of pulsed HEGR is consistent with a power law with a spectral index of –1.74 ± 0.11 in the energy range 100 MeV – 20 GeV. The spectrum does not show any evidence of spectral break atleast upto 20 GeV, unlike all the other HEGR pulsars. Statistics of the pulsed HEGR is too low to do any phase resolved spectroscopy.

The efficiency for conversion of spin-down energy loss into HEGR is calculated to be 0.004, with the assumption that the HEGR are beamed into a solid angle of 1 sr.

(g) PSR B0656+14

This pulsar, being the weakest (a factor of ~ 200 weaker than the Vela pulsar) among all seven HEGR pulsars, could be detected only by employing a novel weighting technique by Ramanamurthy *et al.*, (1996). In the usual pulsar analysis, all gamma-rays carry equal weights in making a phase histogram. In the weighting technique, all gamma-rays do not have the same weight. Each gamma-ray is assigned a weight depending on its energy and deviation of its measured direction from that of the radio pulsars, in conjunction with the calibration parameters published by Thompson *et al.*, (1993). If there are two gamma-rays observed at the same energy, the one whose measured arrival direction deviates less from the true radio position, is given a greater weight. When the authors analysed the EGRET data assigning equal weights to all the gamma-rays (the standard technique), probability for the null hypothesis was 3.9×10^{-3}. Since this is not low enough to be certain that the object is really an HEGR pulsar, the authors re-analysed the data using the weighting technique which resulted in the probability for the null hypothesis being $\lesssim 2.6 \times 10^{-7}$; hence the claim is made that the object is an HEGR pulsar.

Statistics of the number of HEGR photons attributed to the source is very poor - there are only a total of ~ 66 pulsed photons. One has to bear this in mind in judging the results given below. The HEGR light curve exhibits a single peak at the phase 0.21 (radio peak at the phase 0.00). The phase-averaged pulsed HEGR flux is $(4.1 \pm 1.4)\ 10^{-8}$ photons/cm^2/sec at $E > 100$ MeV. A crude estimate of the index of an assumed power-law energy spectrum made by the authors results in a value of -2.8 ± 0.3. The small number of HEGR do not allow a more sophisticated analysis of the total spectrum, leave alone the phase-resolved spectroscopy. There is no evidence for any unpulsed emission. The conversion efficiency for spin-down energy-loss into HEGR is estimated to be 0.001.

3. The high energy gamma-ray pulsars as a population

Prior to the launch of CGRO, one knew the existence of only two HEGR pulsars. Thanks to the EGRET database, the number of HEGR pulsars has gone up to seven. Now, we can begin to treat them all as a 'population' and discuss if their collective observed properties reveal any trends and if the theoretical models are successful in accounting for them.

All the HEGR pulsars seen to date are single spin-powered pulsars; none of them is a binary pulsar. Fierro *et al.*, (1995) searched for pulsed HEGR emission by several of the known binary pulsars without any success.

At a first glance, the HEGR pulsar properties appear very disparate. No two pulsars are truly alike; see Tables 1, 2 and 3. As an example, five of them exhibit two peaks in HEGR emission, each with a different offset from the radio peak position in phase and with different intra-peak phase separations. Two of them show a single peak in HEGR emission; however one is a narrow peak and the other, very wide. Likewise the spectral indices of the energy spectra vary over a wide range from –1.18 to –2.8. The energy spectra of all the pulsars (except that of PSR B1951 + 32) either steepen above differing energies or show a distinct break (PSR B 1706 – 44). The energy spectrum of PSR B1951 + 32 continues, without a break or steeping, to energies beyond 20 GeV. Phase-resolved spectral analysis could be carried out only in the case of the three brightest pulsars: Vela, Geminga and Crab. Here again, the energy spectra relating to the bridge region in phase are harder than those in the peak regions in the case of the Vela and Crab pulsars while in the case of the Geminga, the spectrum relating to the phase region of the second peak is the hardest.

The HEGR fluxes received at the Earth differ by a factor of 200 i.e. by nearly 6 magnitudes in the parlance of optical astronomers. This by itself is not surprising as the pulsars are at different distances from the Earth. However, even the computed HEGR luminosities of the sources differ by 3 orders of magnitude. The inferred conversion efficiencies of spin-down energy-loss into pulsed HEGR vary by a factor of 3000.

On a closer look, however, one begins to notice some trends. The efficiency of conversion of spin-down energy-loss of a pulsar into HEGR appears to increase with the characteristic age of the pulsar from 0.0001 for the youngest (Crab) to 0.31 for the oldest (PSR B1055 - 52). The spectral index of the energy spectrum seems to increase (i.e. the spectrum becomes softer) with increasing surface magnetic field of the pulsar (exception:PSR B1951+32). This is understandable in terms of the larger opacity for high energy photons in the higher magnetic fields and the attendant piling up of HEGR at lower energies. The same line of reasoning also explains why PSR B1509-50 could be seen only at low energies (60 keV - 2 MeV) but not at high energies (30 MeV – 30 GeV); for, the extremely intense magnetic field (1.6×10^{13} G) of the pulsar would have rendered the energy spectrum of the gamma-rays that emerge from the pulsar very soft.

If one ranks all the radio pulsars and the lone radio-quiet Geminga pulsar by the parameter $\dot{E}/D^2$ ($\dot{E}$ is the spin-down energy-loss rate and D, the distance to the pulsar), the topmost five radio pulsars are seen as gamma-ray pulsars if one includes PSR B1509-58. This is a remarkable success rate. It tells us that (i) the higher the $\dot{E}/D^2$, the greater the probability that it emits pulsed HEGR and (ii) there is a good overlap in the geometries of the radio and HEGR beams emitted by the pulsars. Rank 6 is held by the Geminga pulsar which we know is radio-quiet. There are various suggestions in the literature to explain why Geminga is not a radio pulsar: (i) there is no overlap in the geometries of the radio and HEGR beams with the Earth missing the radio beam (ii) radio emission by the pulsar is quenched by some mechanism. Radio pulsars with ranks 13 and 22 are again seen as HEGR pulsars. The question arises why radio pulsars with ranks 7, 8,. . . . . .12 and 14, 15, ...21 are not seen as HEGR pulsars. Either the geometries of the radio and HEGR beams do not overlap in these cases or there are other parameters affecting the production of HEGR by radio pulsars. Nel *et al.*, (1996) analysed 350 known radio pulsars for pulsed HEGR emission using the EGRET database but found no more HEGR pulsars.

The EGRET database shows up (besides other sources) approximately 71 HEGR sources which could not be identified with pulsars, AGNs or other known celestial objects (Thompson *et al.*, 1995), Özel and Thompson (1996) analysed their angular distribution in Galactic co-ordinates and concluded that nearly half of them lie in or near the Galactic disc. It is well-known that the radio pulsars are also distributed in a similar fashion. So one is tempted to conclude that the unidentified HEGR sources in the disc region may be Geminga-like (radio-quiet) pulsars. One is not able to recognize them as HEGR pulsars because there is no input available on the pulsar elements to carry out the periodicity analysis and one does not see them as radio pulsars probably because there is no overlap in the geometries of the radio and HEGR beams. But then this runs contrary to the inference made earlier when we considered the ranking of the pulsars by $\dot{E}/D^2$ parametrization. Probably pulsed radio production is quenched in these objects by some hither-to unknown mechanism.

Theoretical models to explain HEGR production by isolated pulsars fall into two general categories: polar cap models and outer gap models. Both types of models assume that HEGR are produced by a rotating magnetized neutron star with its magnetic axis making an angle with respect to its rotational axis. Briefly stated, in the polar cap models (see Daugherty and Harding, 1994, 1996; Sturner and Dermer, 1994 and reference therein) charged particles are accelerated in the electric fields developed near the polar caps of neutron stars and HEGR are produced by synchrotron emission and curvature radiation by the charged particles. In the outer gap models (see Ho, 1993; Romani and Yadigaroglu, 1995 and references therein), the particle acceleration takes place in the vacuum gaps farther from the neutron star, within and closer to the light cylinder, either by synchrotron radiation or inverse compton scattering by the accelerated $e^{\pm}$ beams and the HEGR are produced.

The various theoretical models do account for some of the observed features but not all; the reader is referred to the discussions in the discovery papers of the various HEGR pulsars already listed, for details. In general the models predict steepening of the energy spectra, appearance of two peaks, the general shape of the HEGR light curves etc. But, when it comes to details, the models fall short of explaining the observations; for example, not a single model predicted the sharp break in the energy spectrum of PSR B1706 - 44 at 1000 MeV (Thompson *et al.*, 1996). Where the models made some firm predictions, for example on the conversion efficiencies, the observations do not agree with them in some cases. Neverthless some of the models are successful in explaining some of the trends in the observed properties of HEGR pulsars which we will mention next.

Harding (1981) modeled the gamma-ray efficiency, η, based on polar cap model described in detail by Daugherty and Harding (1982). In this model, the quantity $\eta\dot{P}^{-1.3}$ is expected to be proportional to $\tau^{1.8}$ where τ is the characteristic age of the pulsar. Figure 3 shows the observations. The straight line, the best-fit line for the first 5 pulsars discovered, is slightly steeper than $\tau^{1.8}$. The observations agree reasonably well with the model except in the case of PSR B0656+14. In a revised outer gap model, Chen and Ruderman (1993) have indicated two allowed regions for HEGR pulsars in the dipole surface field - pulsar period parameter space. While 4 of the 7 HEGR pulsars populate the allowed regions, the remaining three fall just outside the allowed Vela-type region; see Figure 4. It is likely that these too will be brought inside the re-adjusted allowed region in an improved version of the model.

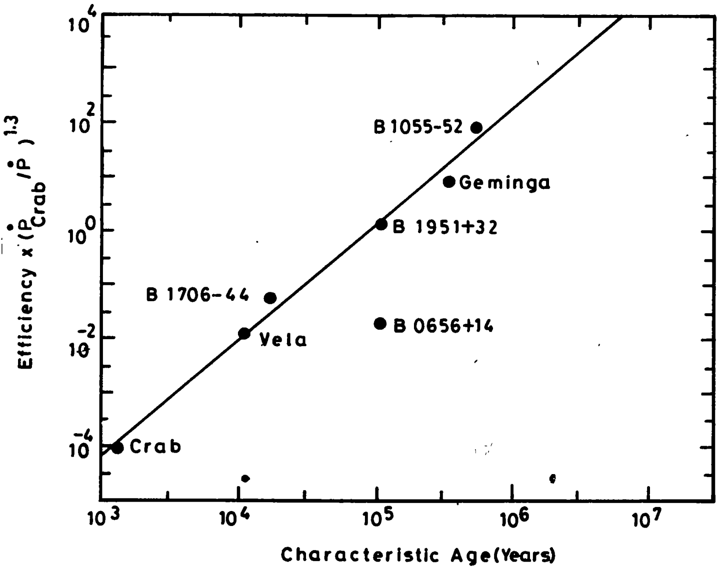

Figure 3. A comparison of the prediction of the polar cap model (Harding, 1981) with the observation, on the variation of the conversion efficiency of spin-down energy-loss rate with the age of the pulsar. The straight line is the best fit for the first five HEGR pulsars detected.

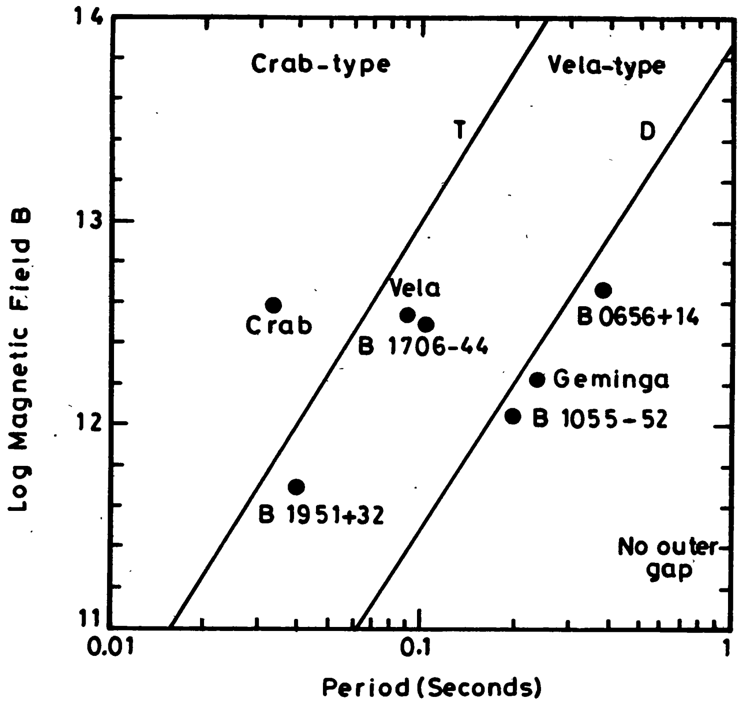

Figure 4. The allowed Crab-type and Vela-type, and the forbidden regions in the magnetic field-pulsar period parametric space, according to the theory of Chen and Ruderman (1993) based on their outer gap model. Positions of the observed seven HEGR pulsars are shown by solid circles.

We end this section by pointing out another trend discernible in the properties of the population of HEGR pulsars. In very general terms, one can expect the HEGR flux received at the Earth from a pulsar to depend on P, $\dot{P}$, D (the distance to the pulsar), B (the surface magnetic field), τ (the characteristic age of the pulsar and Ω (the solid angle of the beam). One can then write

$$\text{Flux} = \text{fn}[D, \{B, P, \dot{P}, \tau, \Omega\}]$$

The quantities in the curly brackets are not all independent of each other. So we re-write

$$\text{Flux} = \text{fn}\ [D, P, \dot{P}]$$

Inspired by the paper by Harding (1981), we tried the relation

$$\text{Flux} \propto \dot{P}^{0.5} / \{D^2P\}$$

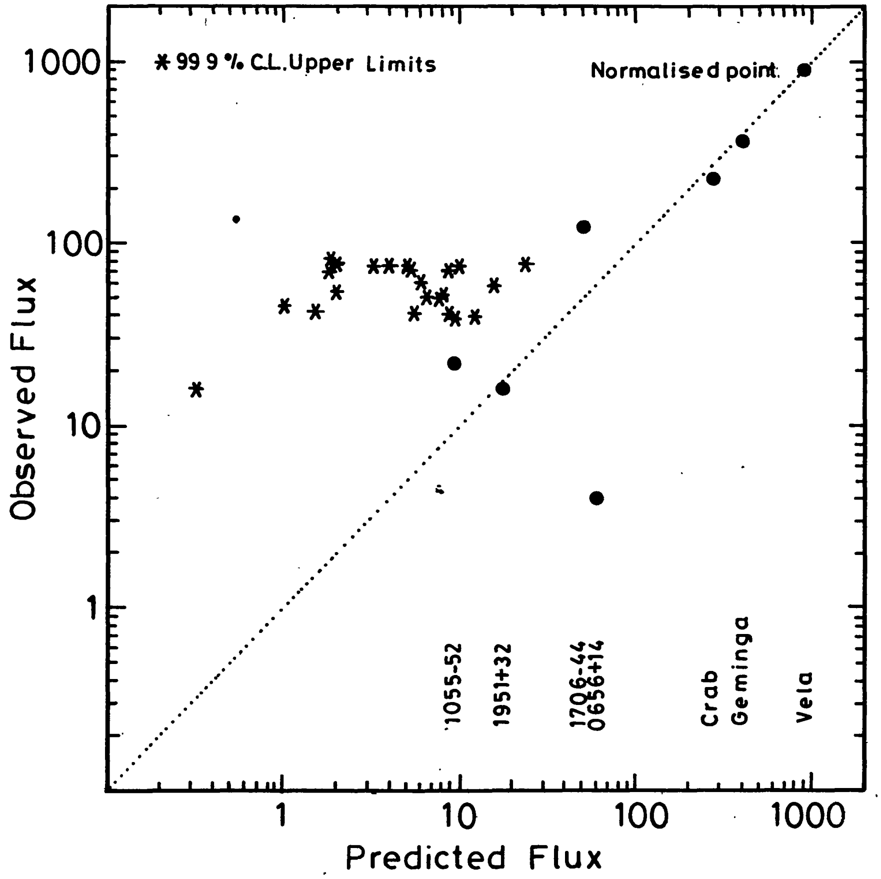

Figure 5. Observed fluxes are compared with the fluxes predicted by an empirical formula (see the text) for the seven detected HEGR pulsars (solid circles). The asterisks are 99.5% C.L. upper limits to the observed flux for several radio pulsars (Thompson et al., 1994).

We fixed the proportionality constant by using the observed values of flux, D, P and $\dot{P}$ of the Vela pulsar. In figure 5, the observed fluxes from the other six HEGR pulsar are compared with the predicted, using this normalisation. One can see that the agreement is good, except in the case of PSR B0656+14. In the case of this pulsar, the HEGR might have gotten attenuated in the very high surface magnetic field, 4.7×10^{12} G, of the pulsar, resulting in a lower flux value. Also, shown in Figure 5 by asterisks are the observed 99.5% C.L. upper limits to the fluxes from several pulsars (Thompson *et al.*, 1994). We note that none of the upper limits are lower than the predicted fluxes. This only points out that a more sensitive detector will, in future, be able to detect most of those pulsars for which we could give only upper limits with the present detectors.

4. Future prospects

The COS-B very reliably identified the Vela and Crab pulsars, Geminga source (not as a pulsar) and perhaps half-a-dozen other sources. The next generation EGRET detector with an improved sensitivity and angular resolution has demonstrated what an improved detector can do, by detecting a total of 129 sources (Thompson *et al.*, 1995). The lifetime of the EGRET detector is coming to an end. The EGRET database has been searched rather thoroughly by a few independent groups for HEGR pulsars. It is unlikely that one can find any more strong HEGR pulsars in the database. However, moderately strong and weak HEGR pulsars may show up if one analyses the data by using non-standard techniques e.g. the weighting technique used by Ramanamurthy *et al.*, (1996). The EGRET team found, in addition, several marginally significant sources. All these sources and many more will no doubt be discovered by a future, improved HEGR detector.

A few groups in U.S.A, Europe and Japan are working on the design of a future HEGR detector which will be more sensitive and will have better angular resolution than the EGRET detector. It is a tough technical challenge. Given the ingenuity and perseverance of the scientists and engineers working on these detectors, success is guaranteed. However, the present global climate for research in basic sciences being what it is, it is doubtful if one can persuade the Governments to fund a satellite to carry the detector into space. One may have to wait atleast 10 years before this fond hope becomes a reality. It is a distant goal.

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