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A search for radio-quiet gamma-ray pulsars in the EGRET data

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Abstract. We are searching for radio-quiet gamma-ray pulsars among the brightest unidentified EGRET point sources. This investigation utilizes the computational resources of the Center for Advanced Computing Research at Caltech to compute Gigapoint power spectra. Multiple frequency derivatives are searched by accelerating event times before computing the Fourier transform. We demonstrate that such a search detects the pulsation of radio-quiet Geminga with 10^{-12} significance directly from 6 days of EGRET data. The remaining unidentified EGRET sources have substantially less signal to noise to support a periodicity search, but can be detected with ~3 weeks of exposure if the pulsar lightcurve has sufficient harmonic content. Only upper limits have been obtained to date. We demonstrate that the error in transforming EGRET event times to the solar system barycenter caused by the inaccuracy of the EGRET position results in a detection at a frequency and frequency derivative different from the true values, but harmonic power is not lost.

Key words: pulsars: general — gamma-rays: observations

1. Introduction

Just as BATSE has intensified rather than resolved the mystery of the gamma-ray bursts, the EGRET all-sky survey has not solved the mystery of the Galactic plane high-energy γ-ray sources. EGRET verifies ~15 COS-B sources (Swanenburg et al. 1981), but the EGRET observations have led to new identifications of only two of them, Geminga (Mattox et al.1996a) and PSR 1706−46. Both are pulsars. In addition, EGRET detects 23 new sources with Galactic latitude $|b| < 10°$ (Thompson et al. 1995). All but one (PSR 1055−52) are unidentified. Also, PSR 1951+32 (Ramanamurpthy, these proceedings) has been found at a low flux level by epoch folding. Thompson et al. (1994) have epoch-folded EGRET data with the ephemerides of 40 radio pulsars which were selected to have a large value of rotational energy loss relative to the square of the estimated distance. No new gamma-ray pulsars were found in that search.

Thus, we have an enigma. The six identified EGRET Galactic sources are all pulsars. But a search of known radio pulsars for gamma-ray emission finds only a small fraction of the EGRET sources. This leaves two possibilities for the identity of the remaining sources: some could either be radio-quiet pulsars like Geminga, or alternatively, they could be a new type of Galactic gamma-ray source. Our search tests the first hypothesis, namely that the sources are gamma-ray loud, but radio-quiet pulsars.

In light of the discovery that Geminga is a radio-quiet pulsar (Bertsch et al. 1992) and predictions that the class of radio-quiet gamma-ray pulsars is potentially large (Yadigaroglu & Romani 1995) we have begun a search for pulsed emission from some of the brighter unidentified EGRET sources.

Simple geometrical models describing the production of gamma-rays in rotation powered pulsars show that there are large ranges of viewing angles where pulsed gamma-rays will be seen with radio emission not beamed into the line of sight to Earth. Romani & Yadigaroglu (1995) show that a large number of gamma-ray pulsars, in fact 2.5× the number of radio-selected gamma-ray pulsars, will be detected *only* at high energies. This implies that ~10 of the unidentified EGRET sources are Geminga type sources, i.e. gamma-ray pulsars without detectable radio emission.

2. The deep periodicity search

Based on the EGRET phase 1 and 2 observations of previously discovered and previously undiscovered gamma ray sources, we have compiled a list of the most promising candidates for deep periodicity searches. Table 1 summarizes the sources which are possibly intense enough for a successful periodicity search. Possible supernova remnant associations are noted since there is a statistical indication

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(Sturner et al. 1996) that unidentified EGRET sources are associated with SNR. To a decent approximation, the significance of the detection of periodicity depends exponentially on N_s^2/N_t, where N_s is the number of modulated source counts, N_t is the total number of counts.

The events for the analysis are choosen from an energy dependent cone of radius $\theta \leq 5°.85\ [E_\gamma/100\ \mathrm{MeV}]^{-0.534}$. At each energy, this includes 68% of the PSF and provides approximately the optimal signal to noise ratio for a timing analysis. The estimated value of N_s^2/N_t for 4 weeks exposure was obtained by scaling the value of N_s^2/N_t found in a fiducial phase 1 exposure for each source. N_s^2/N_t increases linearly with exposure. For the fiducial exposure, N_s was obtained from a point source likelihood analysis (Mattox et al. 1996b) of the E>100 MeV maps. The counts estimate was multiplied by 68% corresponding to the selection described above. N_t was obtained by actually making this selection from the appropriate summary database (using either the SSC QUICKLOOK program or the PULSAR program). times for the nominal positions. The minimum N_s^2/N_t required for detection depends on the harmonic content of the lightcurve. For optimum harmonic content, a N_s^2/N_t of ~50 is required. We expect that our search for periodicity provides more sensitivity than that of Brazier & Kanbach (1996) because we can search up to four weeks of EGRET data coherently.

Table 1. List of EGRET sources targeted for periodicity searches. The coincident supernova remnant is followed by the Galactic position. The flux is in units of $10^{-8}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ $E > 100$ MeV). N_s^2/N_t 4 weeks is the expected value of N_s^2/N_t for a four week exposure on-axis with fresh gas, full telemetry, and full-field operation. This list includes all unidentified sources for which the estimated value of N_s^2/N_t for 4 weeks exceeds ~50.

Name	SNR	l	b	Flux	N_s^2/N_t 4 weeks
J0004+73	CTA 1	119.8	10.5	54	111
J0240+61		135.7	1.2	78	174
J0617+22	IC 433	189.1	3.2	45	75
Geminga		195.1	4.3	366	1524
J1021-58		284.4	-1.2	96	70
J1416-61	G312.4-0.4	312.3	-0.8	100	131
J1744-28	Sgr A East	0.2	-0.2	120	85
J1758-23	W 28	6.7	-0.1	70	48
J1837+59		88.7	25.1	48	173
J1853+01	W 44	34.8	-0.8	70	63
J2019+40	γ Cygni	78.1	2.2	97	136
J2021+37		75.5	0.6	73	103
J2032+40		80.2	0.7	67	100

3. Search strategy

To feasibly perform blind searches, we have implemented the FFT and associated software on massively parallel computers. In view of the spin-down expected of most rotation-powered pulsars, a wide range of frequency derivatives must be searched. For each trial frequency derivative, the search code accelerates the arrival times of the photons corresponding to the expected frequency derivative, $\dot{f}$, performs the FFT, calculates the power spectrum, normalizes it by the global mean power, sums the normalized powers over a range of harmonics corresponding to each fundamental frequency and then saves all candidate frequencies, f_{can}, and frequency derivatives, $\dot{f}_{\mathrm{can}}$ at which the powers exceed pre–determined thresholds.

For each candidate, the precision of f_{can} and $\dot{f}_{\mathrm{can}}$ are limited respectively by the size of an independent Fourier bin and the step size of the frequency derivative grid used. Epoch folds over dense f, $\dot{f}$ grids can be performed in the vicinity of f_{can}, $\dot{f}_{\mathrm{can}}$ to pin down the signal.

We have begun extensive searches on archival data for GRO J1744−28, GRO J2019+40 and GRO J0617+22. To date, we have consumed more than 80 000 CPU node hours, corresponding to about 561 teraflops, on the Intel Touchstone Delta parallel supercomputer. No pulsars older than the Vela pulsar with with large γ-ray modulation are present in these data. Figure 1 shows the phase space which has been searched for GRO J2019+40.

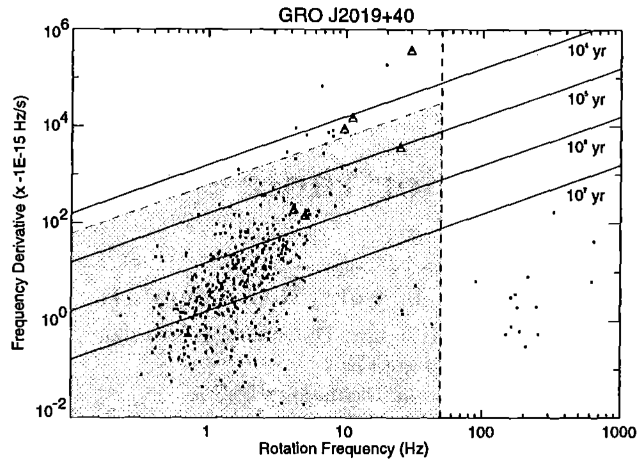

Fig. 1. The $f - \dot{f}$ phase space which has been searched for GRO J2019+40. The 472 pulsars of 558 in the current Princeton catalog (Taylor et al. 1993) which have positive period derivatives are denoted by black dots. The 6 pulsars detected by EGRET are denoted by triangles. They are, in order of decreasing rotation frequency, Crab, PSR 1951+32, Vela, PSR 1706−44, Geminga, and PSR 1055−52. The lines plotted in the figure are lines of constant age for pulsars born at short periods, assuming a vacuum dipole braking law

4. Detecting the periodicity of Geminga

The public Geminga data give us the opportunity to refine our search technique, and to verify the expected sensitivity with the known periodicity of the Geminga pulsar. If the search we propose for the unidentified EGRET sources is worthwhile, then Geminga must be easily detected. The expected value of N_s^2/N_t for Geminga for a four week

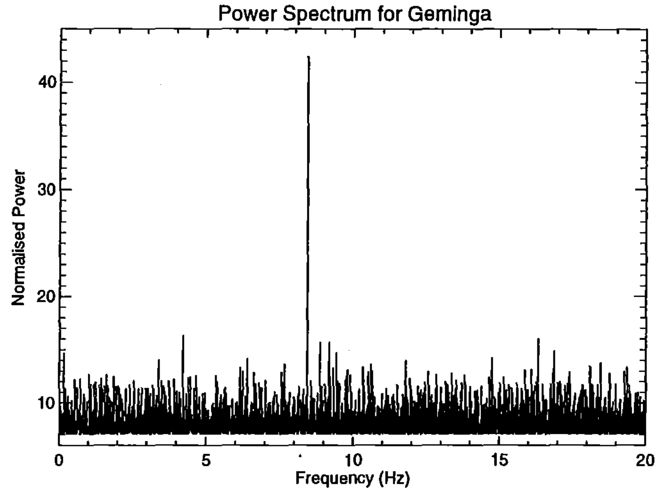

Fig. 2. The power spectrum from an FFT of 2^{28} time bins for the EGRET viewing period 1.0 observation of Geminga. The spectrum has been normalized by the average power, so that the power shown here multiplied by 2 is expected to be distributed as χ_2^2 in the absence of periodicity. The power is not plotted if the normalized power is less than 7. The Geminga pulsar rotation frequency and its 2^{nd} and 4^{th} harmonics are readily apparent at 4.2, 8.4, and 16.9 Hz. The power of the 2^{nd} harmonic dominates because of the shape of the light curve — two nearly equal peaks separated by ~180°

exposure is 1524. This is a factor of 9 larger than that of the most detectable unidentified source in our target list (Table 1).

We used half of the Delta machine (128 nodes) for a Geminga test. This limited the size of the FFT to 2^{28} points. Therefore we have only obtained the power spectrum of the first 6.2 days of the EGRET viewing period 1.0 observation. For a dataset of this length, the spacing we specify between trial frequency derivatives is $\dot{f}_0 = 1.7\ 10^{-12}$ Hz s^{-1}. A search to a $\dot{f}$ as large as the Vela pulsar ($-4\ 10^{-11}$ Hz s^{-1}) requires 25 frequency derivative trials. The trial frequency derivative which comes closest to the actual frequency derivative ($-1.95221\ 10^{-13}$ Hz s^{-1}) is our first trial, with $\dot{f} = 0$. The power spectrum for this is shown in Fig. 2. The calculation took ~3 minutes (6.4 CPU node hours). The X-ray/optical position was used for the Barycenter arrival time transformation (although we demonstrate in the next section that a detection could have been obtained with the EGRET position).

Our current detection process consists of summing the power of 3 adjacent bins for four harmonics. The maximum of this sum for this power spectrum is 81.65. The chance that this is spurious is

$$S = \int_{2\times 81.65}^{\infty} \chi_{24}^2(\xi)\mathrm{d}\xi$$

Numerical evaluation of this integral yields $S = 1.1\ 10^{-22}$. With a search to 100 Hz we made $100 \times 4 \times 6.2 \times 86400 = 2.1\ 10^8$ frequency trials; and 25 frequency derivative trials. The post-trials significance for the search is thus $6.0\ 10^{-13}$. Unfortunately, our Geminga detection is described in these proceedings instead of Nature because of the Rossi Prize work of Jules Halpern with ROSAT data (Halpern & Holt 1992) in the interval between the EGRET data acquisition and its public availability.

5. The effect of position error on the barycenter timing correction

For a timing analysis, EGRET event times are transformed to the arrival times at the Solar System Barycenter. If the position used for this transformation ($\boldsymbol{D}_\text{o}$) deviates from the true pulsar position ($\boldsymbol{D}_\text{P}$), the observed frequency (f_o) will be Doppler shifted with respect to the true pulsar frequency (f_P),

$$f_\text{o} = f_\text{P} + \frac{f_\text{P}}{c}(\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}) \cdot \boldsymbol{V}_\oplus \quad (1)$$

where $\boldsymbol{V}_\oplus$ is the orbital velocity of the Earth ($|\boldsymbol{V}_\oplus| = 10^{-4}c$). The magnitude of this frequency error is

$$f_\text{o} - f_\text{P} < \frac{f_\text{P}}{c}|\boldsymbol{V}_\oplus|\,|\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}| = 10^{-5}\frac{|\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}|}{10^{-2}}\frac{f_\text{P}}{10\text{ Hz}}\text{ Hz} \quad (2)$$

A $|\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}| = 10^{-2}$ radian error in position is typical of the EGRET position uncertainty. This frequency error will not prevent a pulsar detection, however, it is likely to result in a frequency estimate which is significantly different from f_P.

The frequency derivative is similarly affected. Differentiation of Eq. (1) leads to

$$\dot{f}_\text{o} = \dot{f}_\text{P} + \frac{1}{c}(\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}) \cdot (\dot{f}_\text{P}\boldsymbol{V}_\oplus + f_\text{P}\frac{\mathrm{d}\boldsymbol{V}_\oplus}{\mathrm{d}t}) \quad (3)$$

Since $f_\text{P}\frac{\mathrm{d}\boldsymbol{V}_\oplus}{\mathrm{d}t}$ is ~10^5 times larger that $\dot{f}_\text{P}\boldsymbol{V}_\oplus$ an adequate approximation is

$$\dot{f}_\text{o} = \dot{f}_\text{P} + \frac{f_\text{P}}{c}(\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}) \cdot \frac{d\boldsymbol{V}_\oplus}{dt} \quad (4)$$

The magnitude of this frequency derivative error is

$$\dot{f}_\text{o} - \dot{f}_\text{P} < \frac{f_\text{P}}{c}\dot{\theta}|\boldsymbol{V}_\oplus|\,|\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}| \quad (5)$$

$$= 2\ 10^{-12}\frac{|\boldsymbol{D}_\text{P} - \boldsymbol{D}_\text{o}|}{10^{-2}}\frac{f_\text{P}}{10\text{ Hz}}\text{ Hz s}^{-1}$$

where $\dot{\theta} = 2\ 10^{-7}$ rad s^{-1} is the angular velocity of the earth's orbital motion. This frequency derivative error is two orders of magnitude smaller than the Crab $\dot{f}$, so it simply gets swept up in the frequency derivative search. However, it is one order of magnitude larger than the Geminga $\dot{f}$. Therefore even if an $\dot{f}$ smaller than $\dot{f}_\text{o} - \dot{f}_\text{P}$ is suspected, the full range $\dot{f}_\text{o} - \dot{f}_\text{P}$ must be searched because of the position uncertainty.

For a four week exposure, a change in the pulsar second frequency derivative of $\ddot{f}_0 = 6(28 \times 86400)^{-3}$

=4.3 10^{-19}Hz s^{-2} causes a phase change of 2π over the observation. Fortunately, this is an order of magnitude larger than the average Crab second derivative, so it will not be a problem for the 28 day search. Since $\ddot{f}_0$ decreases as the cube of the duration of the observation, this factor must be considered for a coherent analysis of an observation longer than 28 days.

The second derivative of frequency is also affected by a position error. Differentiation of Eq. (5) yields

$$\ddot{f}_\mathrm{o} - \ddot{f}_\mathrm{P} < \frac{f_\mathrm{P}}{c}\ddot{\theta}|\boldsymbol{V}_\oplus|\,|\boldsymbol{D}_\mathrm{P} - \boldsymbol{D}_\mathrm{o}| + \mathcal{O}\left[\dot{\theta}^3\right] \tag{6}$$

$$= 4\ 10^{-19}\frac{|\boldsymbol{D}_\mathrm{P} - \boldsymbol{D}_\mathrm{o}|}{10^{-2}}\frac{f_\mathrm{P}}{10\ \mathrm{Hz}}\ \mathrm{Hz\ s^{-2}}$$

For observation of 2 weeks duration or less, this second derivative error results in a phase change of less than $\pi/4$ between the beginning and end of the observation. Therefore, no substantial amount of harmonic power is lost. We note that the Crab second frequency derivative leads to a phase change of $\sim\pi/4$ during a 28 day observation. Therefore, the second derivative may be ignored in a period search using single EGRET observations. However, a potential second derivative complicates any attempt to combine harmonic power from different observations.

We have demonstrated that the sensitivity of our search (for ~2 week EGRET observations) is not compromised by the uncertainty of the EGRET position. However, we are not able to determine precise values for the intrinsic pulsar parameters from a detection in a single observation. If the timing noise of the pulsar is sufficiently small, the the γ-ray data can be used to determine the position through timing. Mattox et al. (1994) demonstrate that Geminga is located to $\sim1''$ in α and $\sim8''$ in δ with EGRET data. A detection at two different times of the year (with independent $\boldsymbol{V}_\oplus$ and $\frac{\mathrm{d}\boldsymbol{V}_\oplus}{\mathrm{d}t}$) furnishes four measured parameters ($f_{\mathrm{o},1}$, $\dot{f}_{\mathrm{o},1}$, $f_{\mathrm{o},2}$, and $\dot{f}_{\mathrm{o},2}$). The four intrinsic pulsar parameters (f_P, $\dot{f}_\mathrm{P}$ and $\boldsymbol{D}_\mathrm{P}$) can be obtained from these four measured parameters using Eqs. (1) and (4).

6. Summary

We have developed a method which has the potential of finding more radio-quiet pulsars like Geminga with the EGRET data. Initial searches have yielded only upper limits on the extent of γ-ray modulation for pulsars older than the Vela pulsar. We are now optimizing the summing of the power of harmonics with the intention of maximizing the sensitivity of our search. If detections are not obtained, the numerical values of upper limits will be furnished in a later publication after the refined searches have been conducted. If searches with our optimum algorithm do not find pulsation corresponding to ages greater than the Vela pulsar, we may also search at higher frequency derivatives for promising sources.

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