

# SEARCH FOR FAST GALACTIC GAMMA RAY PULSARS

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## ABSTRACT

We have undertaken a program to search for fast gamma ray pulsars ( $P < 1$  s) in OSSE observations of the galactic center, galactic plane, LMC, and selected sources. We have used search strategies optimized for both isolated and binary pulsars. Applied to OSSE observations, these techniques are sensitive to isolated Crab pulsars at the galactic center and binary Crab pulsars in the local spiral arms. To date we have searched for pulsations from (i) known fast pulsars PSR1613-509 in RCW 103 and PSR0540-693 in the LMC, (ii) the gamma ray transient GRO J0422+32 and SN87A in the LMC, (iii) isolated pulsars in the galactic center, LMC, and galactic plane fields in Cygnus and Carina, and (iv) binary pulsars in these same fields. No pulsations have been detected at frequencies between 1 Hz and 4 kHz, with pulse fraction limits as low as 0.1% of total received count rate.

## INTRODUCTION

NRL's Oriented Scintillation Spectrometer Experiment (OSSE), on board the Compton Gamma Ray Observatory, provides spectroscopic and photometric observations of gamma ray sources in the 0.05–10 MeV energy range. One of the goals of the OSSE mission is the search for gamma ray pulsars. Since gamma ray emission is an important aspect of theoretical models of pulsars, the detection or non-detection of these gamma rays will have a significant impact on our understanding of pulsar emission. Prior to the launch of the Compton GRO, the Crab pulsar was the only non-accretion powered pulsar positively detected in the OSSE low energy gamma ray band. Subsequently pulsations from the Vela pulsar<sup>1</sup> and PSR1509-58 in Circinus<sup>2</sup> have been detected with OSSE.

We have undertaken a program to search for fast gamma ray pulsars (pulse period  $P < 1$  s) in OSSE observations of known or suspected fast pulsars, the galactic center, the galactic plane, and the LMC. No dedicated OSSE observations have been undertaken for this program; rather pulsar mode data from selected existing observations are analyzed for the presence of coherent signals. In order to increase sensitivity by using large data volumes, and to increase frequency coverage, this analysis has been carried out on a massively parallel computer.

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## OBSERVATIONS

The four OSSE detectors have  $3.8^\circ \times 11.4^\circ$  (FWHM) fields-of view; each detector has an independent offset pointing capability to permit background measurements and multi-target observations<sup>3</sup>. High time resolution gamma ray data is provided in the OSSE pulsar data modes. Up to eight energy bands can be included in the telemetry allotted to the pulsar mode data packets. Gamma ray events qualified as being in one of these eight energy bands are then processed in either (i) EBE (event-by-event) mode, where a maximum of  $\sim 500$  selected events per 2.048 s packet are time tagged with an accuracy of  $125 \mu\text{s}$ , or (ii) rate mode, where selected events are binned into samples with a selectable sample size between 4 ms and 512 ms.

## ANALYSIS

There are two classes of potential gamma ray pulsars, each requiring a different search algorithm. For the class of known or suspected isolated pulsars, the optimum strategy is to Fourier transform the longest coherent data stretches possible, and to incoherently sum as many of these as are available. Data stretches ranging between a single Compton Observatory orbit ( $\sim 2500$  s) to over 6 days are used depending on the source.

For blind searches, the pulsar has an unknown period and may be located in a binary system with an unknown orbit. If the orbital period is short enough, Doppler shifts in the pulse period will destroy coherence over the term of the observation resulting in the pulse signal being spread over many channels in the power spectrum. We apply a coherence recovery technique<sup>4,5</sup>, in which an optimal one dimensional search through the phase space of possible binary orbits is conducted, and corrections for trial orbits are applied to the data before the Fourier transform is calculated. Coherent data stretches are used that are short relative to trial orbital periods, and no incoherent summations to increase sensitivity are possible; see below for details. We choose data stretches corresponding to a single Compton Observatory orbit; this limits the search to binary systems with orbital periods  $P_{\text{orb}} > 7.1$  hr.

Standard data processing, including data selection and formatting, are performed on the OSSE VAX cluster. The data is then transferred to the NRL Connection Machine Facility. All subsequent analysis, including correction to solar system barycenter, binning of data, coherence recovery transforms, Fourier transforms, and selection of peaks in the power spectrum, are performed on NRL's 16,384-node parallel Connection Machine CM-200 computer with extended memory<sup>5</sup>.

The software has been tested using OSSE observations of the Crab pulsar (isolated pulsar case) and Her X-1 (binary pulsar case). In both tests, the known

pulse was recovered at the expected amplitude and significance.

## COHERENCE RECOVERY TECHNIQUE

Pulsars in a binary system have their pulse frequency Doppler shifted due to the orbital motion of the pulsar. Without correction, this results in a broadening of the pulse signal into many channels of a standard Fourier power spectrum. In the cases under study here, very short pulse periods and very long observations, the signal can be spread over thousands of channels.

Correcting the signal for orbital motion requires accurate knowledge of the orbit. A general circular orbit can be specified by three parameters: projected semimajor axis  $a_{\perp}$ , orbital period  $P_{\text{orb}}$ , and orbital phase at the time origin  $\phi_0$ . In the case where the orbit is unknown, searching all orbits would require searching a three dimensional phase space. This strategy is computationally impractical.

We have used a quadratic coherence recovery technique which involves searching a one dimensional phase space<sup>4,5</sup>. The time of arrival for data,  $t$ , is quadratically transformed to  $t' = t + \alpha t^2$ , where  $\alpha = a_{\perp} \Omega_{\text{orb}}^2 \sin(\phi_0)$  and  $\Omega_{\text{orb}} = 2\pi/P_{\text{orb}}$ . This is mathematically equivalent to approximating the arc of the pulsar's orbit during the observation with a parabola. A one dimensional search over all possible values of  $\alpha$  is then performed — for each value of  $\alpha$ , the data is quadratically transformed and then Fourier transformed. The extreme values of  $\alpha$  searched depend on the assumed mass function for the binary, but are less than  $10^{-7} \text{ s}^{-1}$  for systems comparable to close X-ray binaries with  $P_{\text{orb}} > 7.1 \text{ hr}$ . The quadratic approximation is only good for relatively short data stretches; if the duration of the data stretch analyzed,  $T$ , exceeds  $P_{\text{orb}}/4\pi$  then the quadratic transform will not completely recover the coherent signal into a single spectral channel.

## RESULTS

The limits to the pulse fraction are determined using standard statistical techniques<sup>6</sup>. Each power spectrum is normalized to a value of 2 for Poisson noise (Leahy normalization<sup>7</sup>). If we adopt a  $1 - \epsilon = 95\%$  confidence limit for detection of a coherent signal, then the detection threshold  $P_{\text{thresh}}$  for the highest peak detected in the power spectrum is given by  $\epsilon/N_{\text{trial}} = Q(M P_{\text{thresh}} | 2M)$ , where  $Q(\chi^2|\nu)$  is the probability of exceeding a value of  $\chi^2$  in a  $\chi^2$ -distribution with  $\nu$  degrees of freedom,  $M$  is the number of Fourier transforms incoherently summed, and  $N_{\text{trial}}$  is the number of independent power spectrum peaks searched. For an isolated pulsar,  $N_{\text{trial}}$  is the number of frequency channels searched  $N_{\text{freq}}$ , while for binary pulsar searches involving  $N_{\alpha}$  quadratic transformations,  $N_{\text{trial}} = N_{\text{freq}} N_{\alpha}/4$  (ref. 5).

When no significant peak is detected, the upper limit to the pulse fraction  $A_{\text{UL}}$  is given by  $A_{\text{UL}} = \sqrt{(P_{\text{max}} - P_{\text{noise}})/N_{\text{ph}}}$ . Here  $P_{\text{max}}$  is the peak normalized power

detected,  $P_{\text{noise}}$  is the  $1 - \delta = 95\%$  confidence lower limit for the Poisson noise power given by  $1 - \delta = Q(M P_{\text{noise}} | 2M)$ , and  $N_{\text{ph}}$  is the average number of counts analyzed in each of the  $M$  power spectra. Note that this is the pulse fraction of the total (source plus background) signal. The upper limit to the pulsed flux is  $F_{\text{UL}} = A_{\text{UL}} N_{\text{ph}} / T A_{\text{eff}}$  for detectors with an effective area  $A_{\text{eff}}$ .

## RESULTS

To date, OSSE observations of the galactic center, the Large Magellanic Cloud, several regions of the galactic plane, and several individual sources have been analyzed for the presence of fast gamma ray pulsars. No pulsars, either isolated or in binary systems, have been detected to date. We give upper limits to a selection of our searches in Table 1 and a typical power spectrum in Figure 1.

A typical OSSE observation during the sky survey portion of the Compton Observatory mission last two weeks. A complete search for isolated pulsars requires approximately 2 CPU hours on the CM-200 for each two week observation. A search for binary pulsars requires approximately 6.0 CPU hours for each Compton GRO orbit analyzed at  $125 \mu\text{s}$  resolution, and CPU time scales approximately with inverse time resolution.

The techniques used, when applied to typical OSSE observations, are sensitive enough to detect the Crab pulsar at the distance of the galactic center. The sensitivity to binary pulsars is significantly less, due to the necessity of searching a large volume of phase space corresponding to possible binary orbits. Even so, the Crab pulsar could be detected in a binary within the nearby spiral arms ( $D < 1 \text{ kpc}$ ).

Figure 1 — Power spectrum for the LMC supernova SN87a. This power spectrum is made from incoherently summing 117 power spectra, each of which is the FFT of a 32M point time series with  $125 \mu\text{s}$  resolution. Plotted are the 99% and 90% confidence limits for a single peak. The peaks at 1, 2, and 3 kHz are instrumental.

Table 1 — Flux Limits on Fast Gamma Ray Pulsars

	$P$ (ms)	energy (keV)	$A_{UL}$	$F_{UL}$ ‡
known pulsars:				
PSR0540-693	50.4	60 – 210	< 0.1 %	< 0.34
PSR1613-509	69.3	40 – 190	< 0.09 %	< 0.54
isolated pulsars:				
GRO J0422+32	> 0.25	40 – 170	< 0.2 %	< 0.64
SN87a	> 0.25	60 – 210	< 0.2 %	< 0.44
Galactic Center	> 8	40 – 150	< 0.3 %	< 0.74
Galactic Center	> 2	40 – 165	< 0.7 %	< 1.28
Gal Plane (Car)	> 8	50 – 165	< 0.3 %	< 0.41
Gal Plane (Cyg)	> 8	40 – 135	< 0.7 %	< 1.52
LMC	> 0.25	60 – 210	< 0.2 %	< 0.32
binary pulsars:				
GRO J0422+32	> 0.25	40 – 110	< 1.0 %	< 2.7
Galactic Center	> 8	40 – 150	< 1.0 %	< 2.9
Galactic Center	> 0.5	40 – 165	< 1.7 %	< 5.0
Gal Plane (Car)	> 8	50 – 165	< 0.7 %	< 1.3
Gal Plane (Cyg)	> 8	40 – 135	< 3.5 %	< 9.2

‡  $10^{-3} \gamma \text{ s}^{-1} \text{ cm}^{-2}$

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