Long-term Monitoring of Accreting Pulsars with Fermi GBM

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Using the Gamma ray Burst Monitor (GBM) on Fermi we are monitoring accreting pulsar systems. We use the rates from GBM’s 12 NaI detectors in the 8-50 keV range to detect and monitor pulsations with periods between 0.5 and 1000 seconds. After discussing our analysis approach we present results for individual sources from the first year of monitoring. Updated figures for these and other sources are available at http://gammaray.nsstc.nasa.gov/gbm/science/pulsars/.

1. Pulsar Monitoring with GBM

The full sky coverage of GBM enables long term monitoring of the brighter accreting pulsars, allowing precise measurements of spin frequencies and orbital parameters, studies of spin-up or spin-down rates and hence the flow of angular momentum, and detection and study of new transient sources or new outbursts of known transients.

2. Data Analysis

The analysis of GBM observations of pulsars presents two main challenges: the background rates are normally much larger than the source rates, and have large variations; and the responses of the detectors to a source are continuously changing because of Fermi’s ever changing orientation. We meet these challenges with an empirical background subtraction and extensive on the fly calculations of detector response matrices. The initial step in our analysis consists of screening the NaI detector count rate data to remove phosphorescence events, gamma-ray burst and particle events and intervals of rapid spacecraft rotation. Then an empirical background model is fit to the rates and subtracted off, after which the rates are combined over detectors in a way that results in an estimate of the variable part of the source flux. From these flux variation estimates we conduct searches for pulsations, and monitor detected sources.

2.1. Empirical Background Subtraction

The screened rates in each channel of the 12 NaI detectors are fit with a model with that includes components for a small number of bright sources, pulse stiff empirical model that contains the low frequency component of the remaining rates. The source models are computed from a model flux spectrum using time dependent response matrices. One fit is made for each channel with the normalization factors for the bright sources common to all detectors, but with the stiff model parameters (a statistically constrained spline) independent for each detector. In Figure 11 we show an example fit for and residuals for one channel and detector. The model successfully fits the occultation steps of Sco X-1, and the overall background trend underlying the pulsation of GX 301-2 which is evident from the residuals.
2.2. Estimated Flux Variations

For a given source we obtain from the NaI detector rate residuals an estimate of the variable part of the source’s flux. Using a model of the source spectrum and the time dependent detector responses we compute for a given channel the source induced rate \( \mu_{ik} \) expected in detector \( i \) at time \( t_k \) if the source has unit flux in the channels energy range. The variable part of the flux \( \Delta F_k \) is then estimated by minimizing

\[
\chi^2_k = \sum_i \frac{(\Delta r_k - \mu_{ik} \Delta F_k)^2}{\sigma_k^2}
\]  

(1)

where \( \Delta r_k \) is the residual rates and \( \sigma_k \) their errors.

2.3. Pulse Searches

We have implemented two different pulse search strategies, daily blind searches, and source specific searches.

For the daily blind searches we compute fluxes from a day’s data for 24 source directions equally spaced on the galactic plane. For each direction we do an FFT based search from 1 mHz to 2 Hz. These provide us sensitivity to previously unknown sources, or sources where we have poor estimates of the pulse period. When we detect a source we determine a coarse estimate of the source’s galactic longitude based on the longitude with the highest power. The latitude can also be constrained by mapping the power over a grid of source directions.

Source specific searches are made over small ranges of frequency and sometimes frequency rate based on phase shifting and summing pulse profiles that are made from short intervals of data, using barycentered and possibly orbitally corrected times. They provide higher sensitivity than the blind searches because of the smaller search ranges and the use of source specific information such as the location, orbital parameters and flux spectrum.

2.4. Phase Averaged Flux

Since our background subtraction removes the phase averaged flux, this must be determined from Earth occultation measurements. For a discussion of GBM Earth occultation measurements see C. Wilson-Hodge et al. in these proceedings [1]. Figure 2 shows the correlation between pulsed flux and the total flux from Earth occultations for Vela X-1. Here we show the mean-minimum (or "area") pulsed flux.

3. Detected Sources

To date we have detected 17 accreting pulsar systems. In Figure 3 we show how these sources are distributed in the Corbet diagram, which tends to separate classes of sources. Four of detected sources, Cep X-4, A 1118-616, Swift J05131.4-6547 (in the LMC), and MXB 0656-074, are not shown on the figure because their orbital periods are unknown. These are all
transients sources that are known or suspected Be/X-ray pulsar binary systems.

### 3.1. Be/X-ray transients

We have detected outbursts from the Be/X-ray pulsar systems EXO 2030+375, Cep X-4, V0332+53, A0535+26, MXB 0656+072, Swift J0513.4-6447 (in the LMC), GRO J1008-57, A1118-615, and 2S 1417-624. These sources show two types of outbursting behavior. Type I consists of series of several outburst all occurring near periastron passage in their eccentric orbit. These “normal” outbursts typically have luminosities of $10^{36} - 10^{37}$ erg s$^{-1}$. Type II consists of a single “giant” outburst, often with super-Eddington peak luminosity, which last for several orbital periods.
In Figure 4 we show the GBM spin frequency and pulsed flux history of EXO 2030+375 which shows a good example of the type I behavior. In Figure 5 we show the GBM pulse frequency and pulsed flux history of A 1118-615, which had a single giant outburst (Type II behavior). Finally in Figure 6 we show the GBM spin frequency and pulsed flux history of A 0535+26, which shows a mixed type I and II behavior with a series of normal outburst leading to a giant outburst which is still in progress. In these and the following figures the r.m.s. pulsed flux is used.

3.2. Disk-Fed Supergiants

We detect one system, Cen X-3, with a supergiant companion that is overflowing, or nearly overflowing its Roche-lobe, resulting in a persistent accretion disk. The GBM spin frequency and pulsed flux history for Cen X-3 is shown in Figure 7. Cen X-3, an eclipsing binary, shows a remarkable “torque switching” behavior with persistent spin-up alternating with intervals of persistent spin-down, with relatively short transitions between the two states. The torque behavior is not simply correlated with the flux.

3.3. Wind-Fed Supergiants

We have detected four systems with supergiant companions where Roche-lobe is underfilled, within the accretion flow from the companion in the form of a stellar wind. These are Vela X-1, GX 301-2, 4U 1538-52, and OAO 1657-415. In Figure 8 we show the GBM spin frequency and pulsed flux of Vela X-1. This source, which is an eclipsing binary, is the prototypical wind accretor. The frequency history is consistent with a random walk, or white torque noise. In Figure 9 we show the GBM spin frequency and pulsed flux of OAO 1657-415, also an eclipsing binary. In contrast to Vela X-1, it shows torque switching, suggesting that an accretion disk which is stable for months forms from the companions wind.

3.4. Persistent LMXBs.

We have detected three accreting pulsars with low mass companions, 4U 1626-67, Her X-1, and GX 1+4. The characteristics of each are unique. 4U 1626-67 is an ultra-compact binary with the companion overflowing its Roche-lobe resulting in an accretion disk. For the GBM observations of this source see A. Camero-Arranz et al. in these proceedings [3]. Her X-1 is an
2009 Fermi Symposium, Washington, D.C., Nov. 2-5

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OAO 1657-415

26.95
26.96
26.97
26.98
26.99

Frequency (mHz)

54700
54800
54900
55000
55100
55200

Time (MJD)

12-50 keV Pulsed Flux (keV cm$^{-2}$ s$^{-1}$)

Figure 9: Frequency and pulsed flux history for the eclipsing wind-fed supergiant pulsar OAO 1657-415 ($P_{\text{orbit}} = 1.70 \text{ d}$, $P_{\text{spin}} = 31.24 \text{ s}$).

eclipsing Roche-lobe overflow system. Obscuration of the pulsar by the accretion disk results in a 35 day flux cycle of a “Main-on” state, off state, “Short-on” state, and another off state. The spin-frequency and pulsed flux history is shown in Figure 10. GX 1+4 is a symbiotic binary, with the pulsar in a wide orbit accreting from the wind of its red giant companion. The GBM pulse frequency and pulsed flux history are shown in Figure 11. These observations show persistent spin-down, with the spin-down rate having no clear relationship to the pulsed flux. The long-term history of the GX 1+4 pulse frequency is shown in Figure 12 which shows a change from spin-up to spin-down in 1983, with only two short returns to spin-up since.

Figure 10: Frequency and pulsed flux history for the eclipsing LMXB pulsar Her X-1 ($P_{\text{orbit}} = 1161 \text{ d}$, $P_{\text{spin}} = 155 \text{ s}$).

4. Conclusion

We have established a pulsed source monitoring system which uses the Fermi GBM data to rapidly detect previously unknown or newly active accreting pulsars, and track the behavior of all detectable pulsars. This system has two components: 1) a daily blind search for pulsed sources, and 2) a monitor of known sources, which uses narrow band pulse searches specific to each source. To date we have detected 17 accreting pulsars. For each of the sources detected we are producing long term histories of the pulse frequency, flux and pulse profile in three energy channels. The plots in Figures 4 to 11 are taken from these history files. Updates of these figures and those for other sources may be found at http://gammaray.nsstc.nasa.gov/gbm/science/pulsars/.

Figure 12: The long-term pulse frequency history for GX 1+4.
We are currently monitoring five sources that we have yet to detect, and will be regularly increasing the number of sources in our monitoring catalog.

Acknowledgments

M.H.F. acknowledges support from NASA grant NNX08AG12G.

References

[1] Colleen Wilson-Hodge et al., “All-Sky Earth Occultation Observations with the Fermi Gamma Ray Burst Monitor,” Proc. Fermi Symp., eConf C091122, 2009
[2] L. Stella, N.E. White & R. Rosner, “Stellar Wind Accretion and the Long-Term Activity of Population I Binary Systems Containing an X-ray Pulsar,” ApJ, 308, 669-697, 1986.
[3] A. Camero-Arranz et al., “Discovery of a New Torque Reversal of the Accreting X-ray Pulsar 4U 1626-67 by Fermi/GBM,” Proc. Fermi Symp., eConf C091122, 2009