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Long-term Source Monitoring with BATSE

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ABSTRACT

The uncollimated BATSE large area detectors (LADs) are well suited to nearly continuous monitoring of the stronger hard x-ray sources, by use of Earth occultation for non-pulsed sources, and time series analysis for pulsars. An overview of the analysis techniques presently being applied to the data are discussed, including representative observations of the Crab Nebula, Crab pulsar, and summaries of the sources detected to date. Results of a search for variability in the Crab Pulsar pulse profile are presented.

1. Introduction

The full-sky, uncollimated field of view of the BATSE detectors, which is required to provide its burst observation and localization capabilities, also enables observations of objects with deterministic source variability, either due to intrinsic source periodicities, or via sampling of source intensity by Earth occultation. The pre-launch estimated sensitivity of both techniques may be found in Fishman *et al.* (1989). Although these sensitivities are much less than that of OSSE, the fact that these observations may be made frequently throughout the GRO mission are expected to add greatly to the understanding of the stronger low-mass and high-mass x-ray binaries, by determination of correlations between intensity states, $\dot{p}$ values, and pulse profile variations.

2. Occultation Method

The analysis method presently being applied to the BATSE data on a daily basis is as described by Fishman *et al.* (1989). The details of the method, with an evaluation of sensitivity currently being obtained, along with observations of an outburst from

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Monitored Occultation Source Candidates

Source Name	Det.
1E1024-57	
3C279	
4U0115+634	
4U1700-37	*
A0535+26	
Aql X-1	
Crab Nebula	*
Cen A	*

Source Name	Det.
Cen X-3	
Cyg X-1	*
Gal. Ctr. Region	*
GX301-2	*
GX339-4	*
Her X-1	
Sco X-1	*
Vela X-1	*

Table 1. Data have been routinely searched for the listed sources since the beginning of science operations. Emission has been detected from locations consistent with these source directions for those objects marked by an "*".

GX339-04 are presented in Harmon *et al.* (1991). Large Area Detector (LAD) data with 2.048 s time resolution and 16 energy channel resolution are always available for each detector (the CONT data type). A simple linear model of the background is applied at the known times of occultation of a candidate source, with the step amplitude determined by the fit.

2.1. Analysis Status

Two programs are run daily on the LAD CONT data type. Intensity and coarse spectral histories are being maintained on ~30 sources that are either measurable on that timescale, or are previously known transient sources which may be expected to flare during the lifetime of GRO. Table 1 lists a sample of the objects, with those that have exhibited significant fluxes identified. The association of the emission with the indicated objects is based on the consistent spectral indices obtained for them, the careful exclusion from the measurements of occultations when other sources are present elsewhere on the limb of the Earth, and observed source periodicities in some cases.

Additionally, a search is made for significant step-like features that occur at times different from the expected sources. To date, no new sources have been detected.

A measure of the systematic errors in these measurements is obtained by daily measurements of the Crab Nebula region. Figure 1 shows a time history of the source flux for an interval during which the GRO pointing was fixed. The BATSE values are within 10% of previous measurements (Jung, 1989) . The best fit to that data was a broken power law, while the present analysis uses a single power law over the indicated range. This is, in part, the reason why the BATSE measurement is somewhat higher. Additionally, atmospheric scattering is not presently a component of the detector response matrices that have been used. While the scattering geometry at times of source occultation is not the most severe

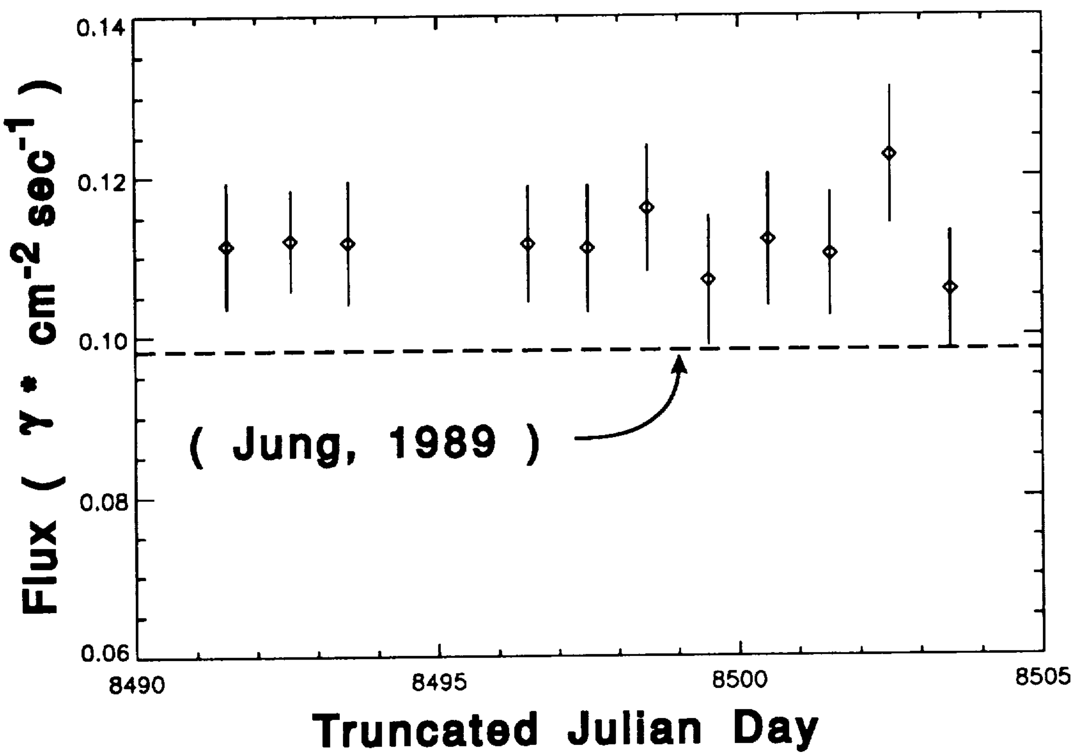


Figure 1. Time history of the Crab Nebula flux obtained using the occultation method. The photon flux has been computed by folding a single power law model spectrum through the BATSE LAD detector response matrices. The integrated spectrum of Jung *et al.* (1989) is shown for comparison.

case, it may produce a significant increase in the apparent source intensity.

With the present, simple model of the background, and the limited integration times used before and after the source emersion/immersion, a source ~10% as strong as the Crab Nebula is detectable in data summed over 1 day. Background modeling studies that are in progress are expected to permit much weaker sources to be monitored.

A representative Crab count spectrum obtain by the BATSE LADs for a 2 week GRO pointing is shown in Figure 2.

3. Pulsed Source Analyses

With the nearly 2π steradian viewing of each LAD, BATSE represents a significant resource for monitoring pulsating objects. The data types useful for this purpose are listed in Table 2. The integration times listed are principally limited by the solar and magnetospheric disturbances to the data on the day(s) to be utilized. During the present high solar activity, major portions of the dataset are undesirable, due to counting rate disturbances which would produce artifacts for any pulse profiles obtained.

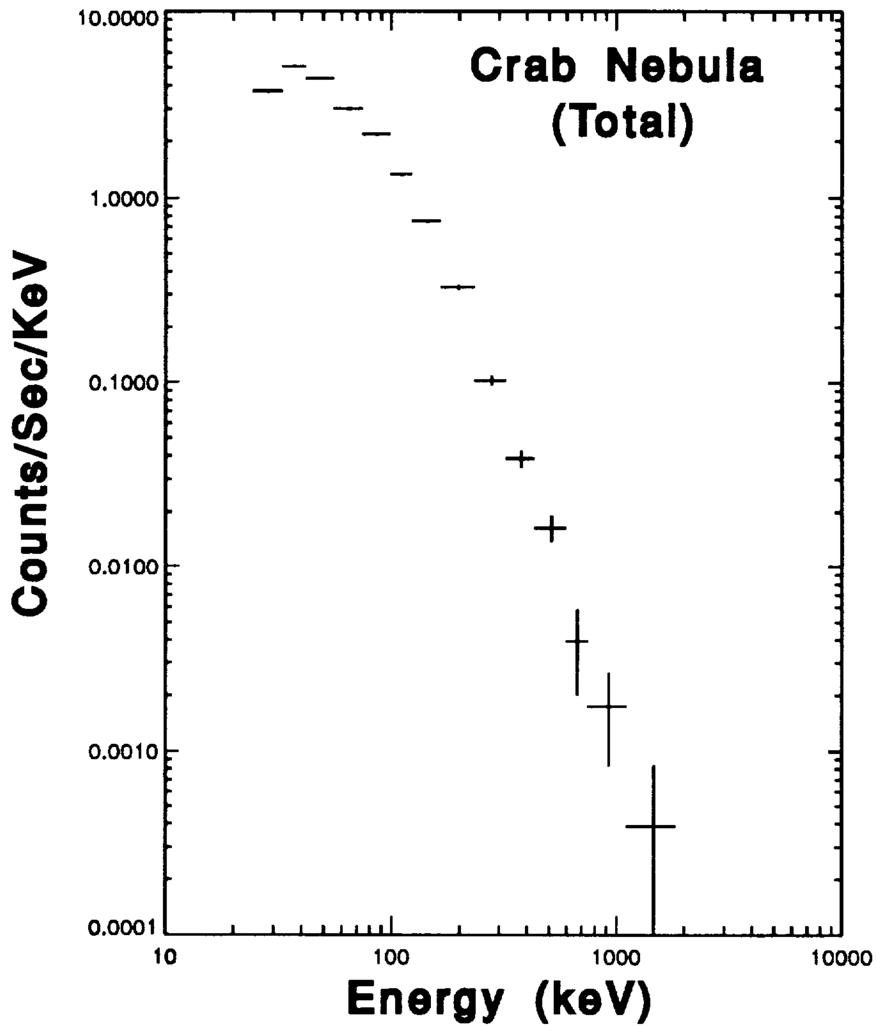


Figure 2. Count spectrum of the Crab Nebula total flux, for a single 2-week GRO viewing interval from Truncated Julian Day (TJD) 8490 to 8504.

3.1. Long-Period Sources

For pulsed sources which can be adequately measured using $\sim$1s time resolution, the BATSE data are especially well suited. As indicated in Table 2, 4 energy channel data with 1.024s time resolution and 16 energy channel data with 2.048s time resolution are continously available for each LAD, except during the South Atlantic Anomaly. This makes it possible to search for periodic signals in the dataset without any need for advance planning.

Analysis tools based on oversampled FFT analysis of DISCLA data which have been filtered in both time and frequency domains are being developed by Guest Investigators T. Prince & J. Grunsfeld . Analysis is performed on each LAD detector individually, and also on appropriate combinations of detectors, to optimize viewing for all regions of the sky.

Pulsed Source Data Types			
Data Type	Time Bins	Energy Chls.	Daily Int. Time
DISCLA	1.024 s	4	50k - 80k s
CONT	2.048 s	16	50k - 80k s
PSRn	Period/64	16	10k - 20k s (Per Source)

Table 2. BATSE data types useful for pulsed source analysis. PSRn data types, which provide readouts of data folded on-board at the approximate period of interest, must be scheduled in advance. Present usage provides data for 4-6 objects per GRO viewing period.

To date, data for about 18 days have been processed as part of this software development effort. In that limited set of data, the following sources have been detected: Her X-1, 4U0115+63, Cen X-3, 4U1627-67, OAO1657-41, GX 1+4, Vela X-1, and GX301-2. Daily processing of the data with this tool has recently begun.

An independent analysis has been performed by Finger *et al.* (1991) of Cen X-3, using both DISCLA and on-board folded data.

The strongest x-ray binary objects are readily observed as signals with amplitudes several percent of the background counting rate in the raw telemetry data. For these objects, direct epoch-folding of the DISCLA or CONT data is a satisfactory analysis method if data from times of events with rapid time variations from unrelated processes are removed. These variations can be produced by gamma-ray bursts, electron precipitation events, solar flares, and phosphorescense events from high-Z cosmic ray interactions. To avoid artifacts in the pulse profiles from more subtle background variations, it is planned in the future to use data that have been "cleaned" as part of the FFT analysis mentioned in the previous section.

An observation of Vela X-1 during an ~8000 s long outburst is shown in Figure 3, demonstrating the BATSE capability to provide high-quality measurements of the emission state of moderate-to-bright sources on a *continuous* basis, except for times of Earth occultation.

3.2. Short-Period Sources

For periods that cannot be observed using the above data types, BATSE operates two controllers in its Central Electronics Unit (CEU), which can be scheduled to fold 16 energy channel data at the approximate observed period of an object, to the nearest microsecond, from a selectable subset of LADs or SDs. The sensitivity for the LADs is shown in Figure 4, based on an amount of data typical for a 2-week GRO pointing.

Since data from several detectors may be combined before on-board folding, it is necessary for the detector gains to be balanced (this need exists also for BATSE's burst location

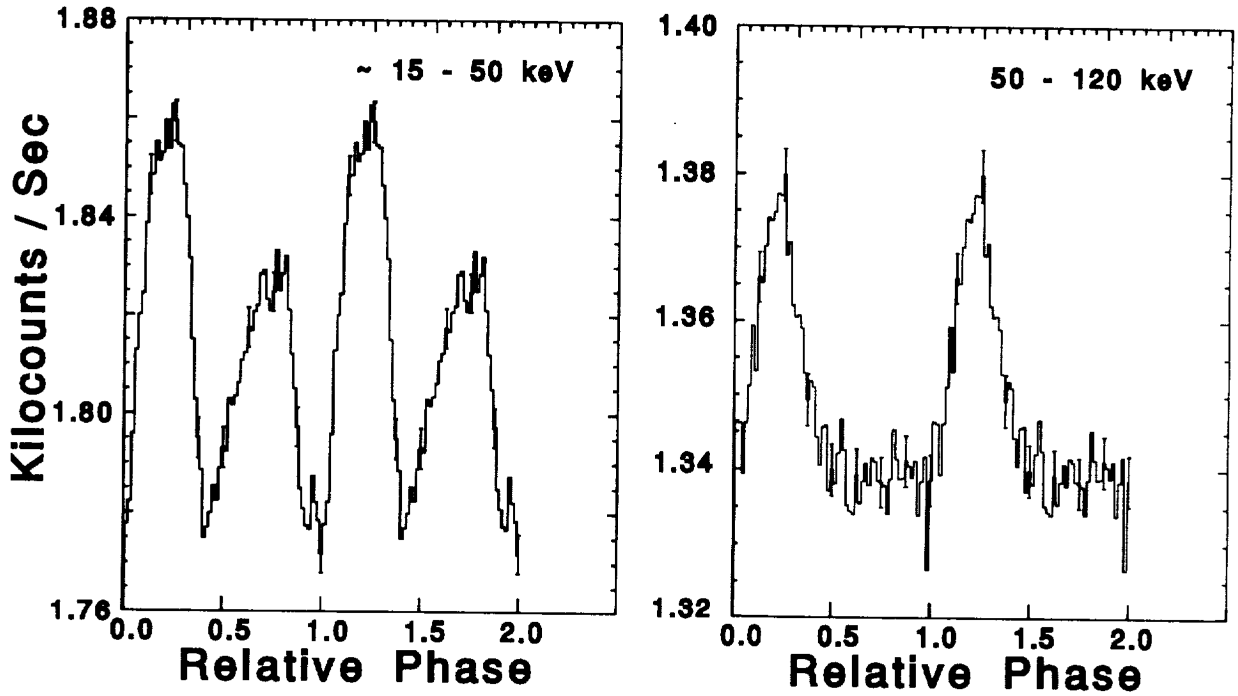


Figure 3. Pulse profile for Vela X-1, during a flaring episode on TJD 8432 for two different energy ranges.

technique). Gain is controlled on-board by locating the atmospheric 511 keV line in each LAD spectrum readout, typically obtained every 5 minutes. Individual detector gains are stable over 100 days or more to about 1%; gain balance is best near the calibration energy (within 2%), degrading to ~8% at 130 keV, still better than the intrinsic energy resolution at that of energy of about 30%.

3.2.1. Pulsar Hardware Usage

Since the sensitivity of BATSE is much less than that of OSSE for energies greater than OSSE's threshold energy of ~60 keV, it is not the best use of the BATSE on-board pulsar controller to search for γ-ray emission from candidate short-period radio pulsars. The ability of BATSE to perform such a search for any GRO orientation is not expected to be of benefit for this type of object, since they would not be expected to have strong amplitude variations over time. The most suitable usage is to frequently monitor the brighter objects, with sufficient exposure to provide spectral information for those sources. The on-board exposure obtained for Cen X-3, analyzed by Finger *et al.* (1991), is just sufficient for spectral analysis when the source is about 10% of the Crab pulsed flux. Thus, the number of objects which can be monitored with this data type is limited. Any object with a period suitably measured using the CONT data can obtain a much longer integration time with that data type. Table 3 lists the sources for which data have been collected to date. While it is

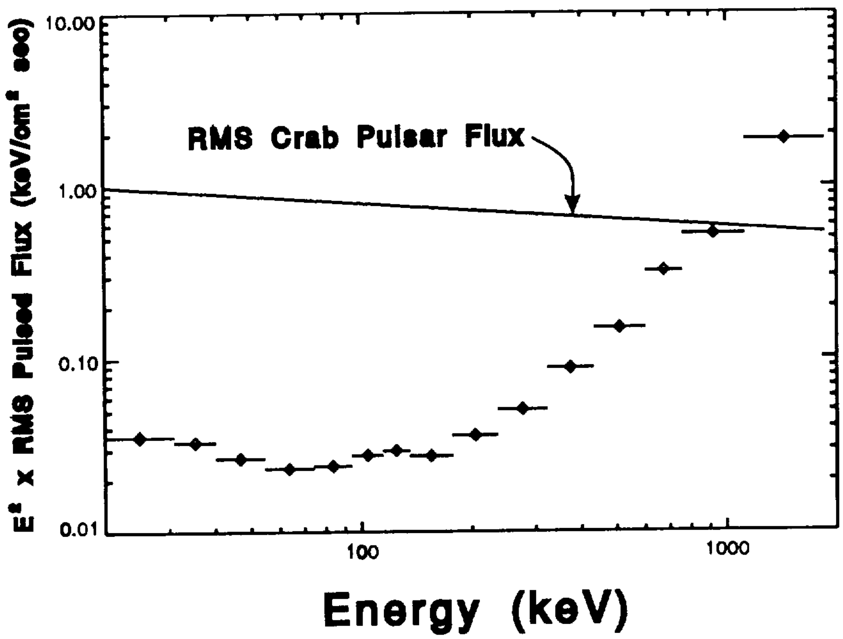


Figure 4. Pulsed source detection efficiency of the BATSE LADs for a 100,000 s exposure time. This sensitivity applies to both on-board and ground folded data, for a pulsar with a Crab-like pulse profile

possible to select the Spectroscopy Detectors (SDs) for on-board folding, it is usually more advantageous to utilize the LADs, due to their much larger area. The SDs have sensitivity above 1 MeV (Fishman *et al.* , 1989) just adequate to monitor a source as bright as the Crab pulsar.

4. Crab Pulsar Analysis

Data collected for the Crab pulsar consist of 8.192 s time integrations (243 folding periods, typically 33392 μs) for 16 energy channels, with 64 phase bin resolution. The start time of the accumulation is time-tagged using the on-board GRO clock, latched and stored to an accuracy of 1/64 ms. The absolute time specification for that clock is better than 0.1 ms. Using the JPL DE200 ephemeris and the GRO position (known to better than 30 km), the Solar system barycenter (SSB) arrival time of the midpoint of the accumulation is determined. Using the source ephemeris provided by Taylor *et al.* (1991), the phase is determined for each of the 64 bin boundaries, centered on the midpoint accumulation time (*i. e.* , the accumlated counts are treated as if they were all obtained during the central "fold"). The counts are then summed in 64 phase bins fixed in the SSB, with counts split linearly between those bins if the input bin phase edges span adjacent bins.

An example of the obtained pulse profile is shown in Figure 5, and is consistent with previous observations of the Crab, as found by Mahoney *et al.* (1984) and Wilson *et al.*

BATSE Pulsed Source Obseravations
Folded-on-Board Data Obtained

Source Name	Det.
Crab Pulsar	*
Vela Pulsar	
Cen X-3	*
SMC X-1	
Her X-1	*
(1957+20)	
(4U0115+63)	

Table 3. List of objects for which BATSE folded-on-board pulsar data has been obtained. Approximately equal exposures have been obtained for all sources except for those in parentheses, which were only present in the schedule for one viewing period. All objects are NOT viewed within every GRO viewing period.

(1983).

The first peak appears to be somewhat softer than the second. A counts spectrum for the two peaks is shown in Figure 6, and shows that this difference is only marginally significant.

4.1. Pulse Profile Variability Search

A search was made on a 0.25 day timescale for variations in the pulse profile of the Crab pulsar for all data obtained on that source from TJD 8370 - 8504. A 64-bin template was formed by minimizing χ^2 bin-by-bin over a large set of average-subtracted 0.25 day profiles, for 4 integrations over energy independently, since the pulse shape is not constant over energy. Since the energy edges of the 16 channels were changed on TJD 8405, and the radio ephemeris for the source was fit separately after that date, the analysis was done in two parts, divided at that date.

In a given energy channel, for the kth 0.25 day interval, phase bin i contains $C_k(i)$ counts. A χ^2 statistic, χ^2_E, is formed,

$$\chi^2_E = \sum_{k,i} (C_k(i) - M_k - \alpha_k \cdot T(i))^2/\sigma^2_k(i) \equiv \sum_k \chi^2_k,$$

where M_k is the mean counting rate for interval k over all phase bins i, $T(i)$ is a template formed by minimizing χ_E for each bin i, obtaining in the process a set of amplitude coefficients, α_k.

Since the phase bins are not independent, due to the splitting of counts between bins, the χ^2 distribution is not that normally obtained. The mean value per degree of freedom (dof) is approximately 2/3. The distribution expected has been computed, taking this

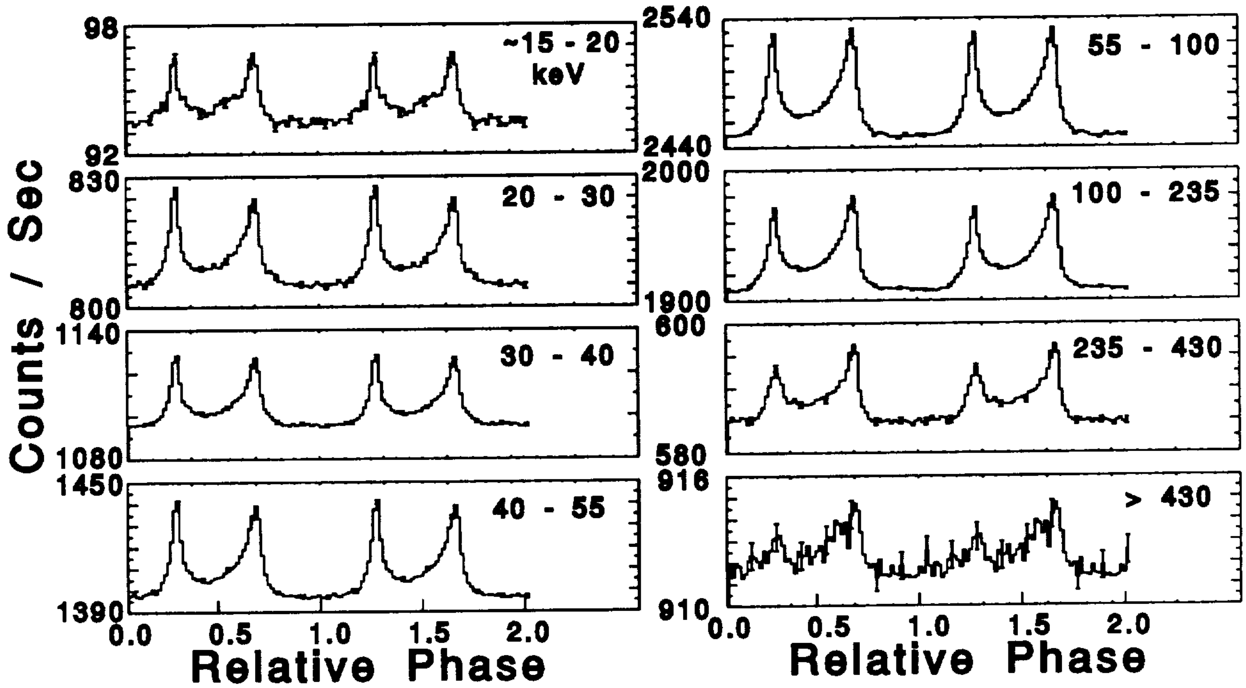


Figure 5. Pulse profile for the Crab Pulsar obtained for a 2-week GRO pointing from TJD 8490 to 8504, for the indicated energy ranges. The integration time for this exposure was 144,800 s. The data were combined on-board for two detectors, at angles of 34° and 54° from the detector normals.

into account. For data from TJD 8370 - 8405, no significant departures from the expected distribution are observed. Figure 7 shows a time history of the observed χ^2/dof for TJD 8406 - 8504. The histogram of these values is shown in Figure 8, along with the expected distribution. In each of the lower 3 energy intervals, there appear to be significant departures from the mean template. The contributions to χ^2_k are found to be primarily from the rising and falling edges of both peaks in the pulse profile.

Given the large viewing angle of the BATSE detectors, it is likely that atmospherically scattered contributions to the pulse shape are the cause of these variations. The time delay for source photons that scatter from as far away as the limb of the Earth are delayed by about 7 ms from those directly incident. While the observed falltime after the second pulse of about 1.5 ms demonstrates that scattering is not a large contributor to the signal, it may be sufficient to produce these small variations.

Data for the Crab are always obtained starting near the same point in inertial space, which represents different geometries relative to the Earth's atmosphere over the course of the precession period of about 52 days. The broad feature between TJD 8420 and 8470 may thus also be an indication of atmospheric scattering effects.

Another potential cause of pulse profile shape changes is the variety of exposure angles to the detectors used to observe the source over this interval. Since the spectral differences over phase for this source are not large, this is thought to be a less important contributor

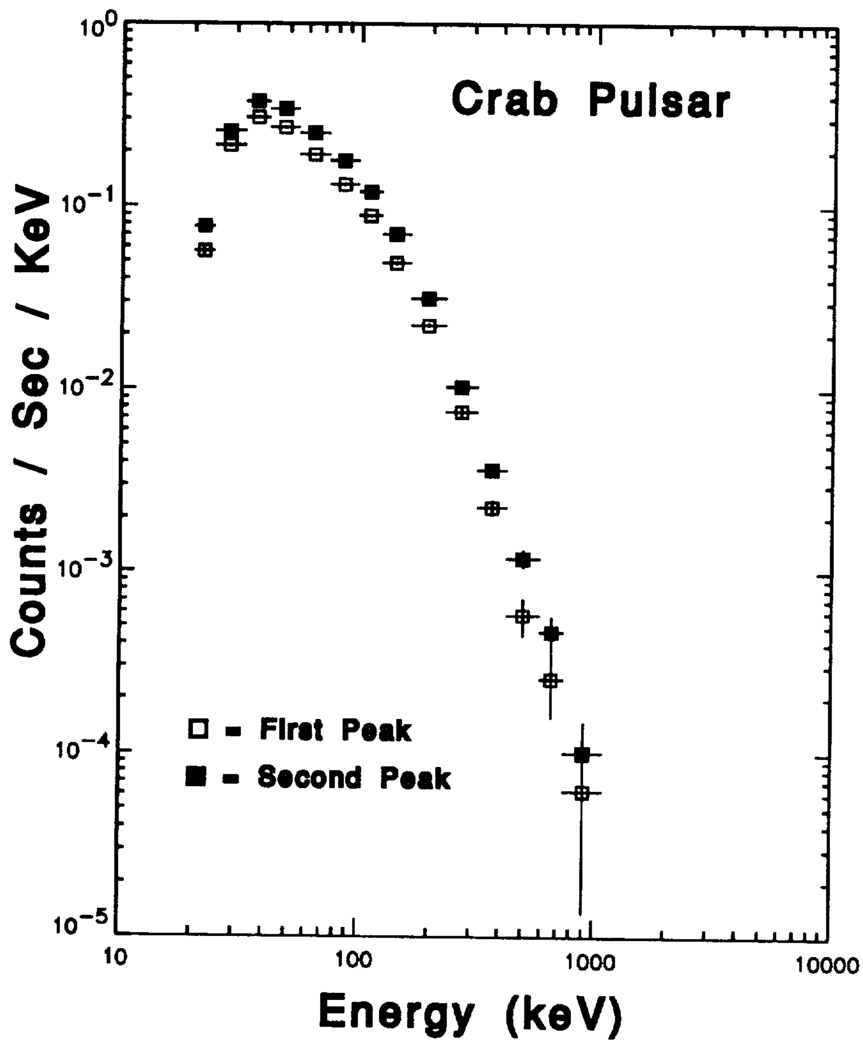
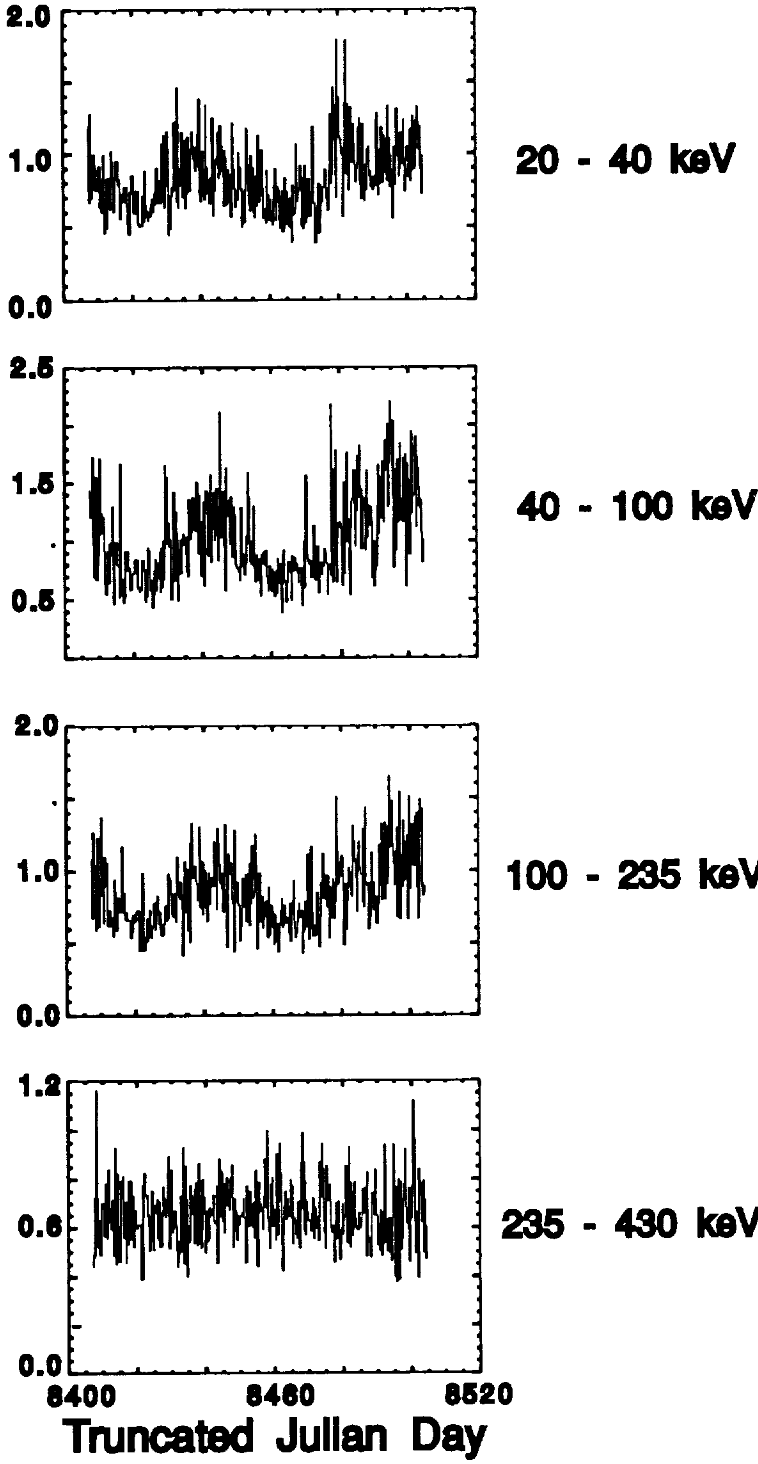


Figure 6. Count spectrum of the Crab pulsar for TJD 8490 to 8504. Peak 1 is defined as phases 0.19 to 0.38; peak 2 as phases 0.50 to 0.69, relative to zero phase as shown in Figure 5.



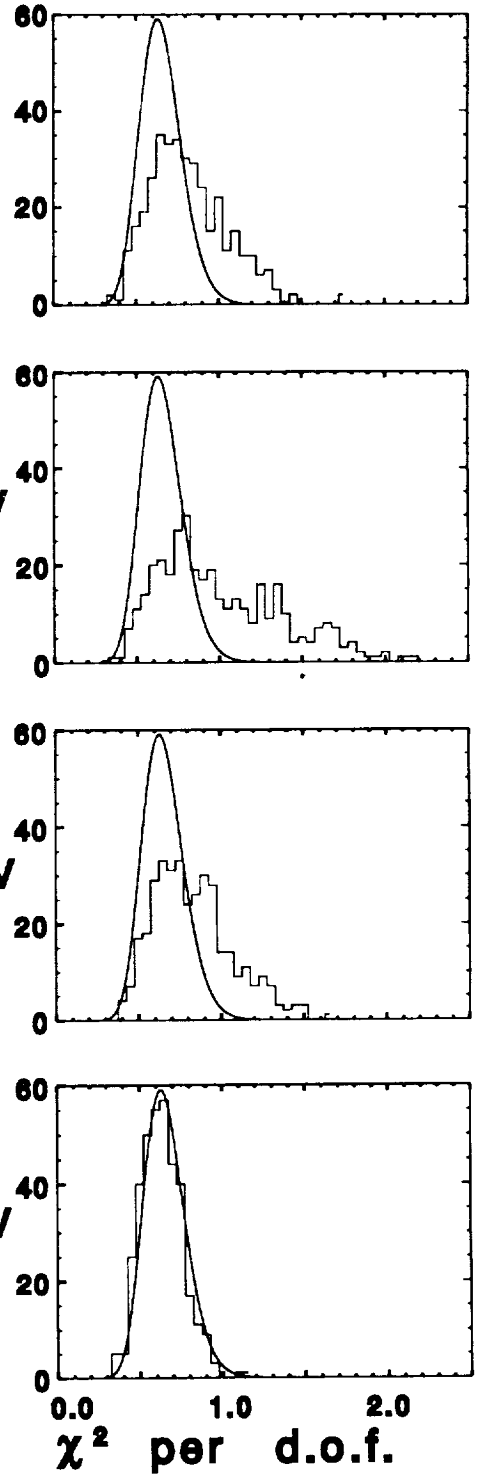


Figure 7. Time history of χ_k^2 per dof for each 0.25 day interval, for departures from a best-fit template derived from the data. The abscissa is the χ^2 value.

Figure 8. Histogram of χ^2 per dof. The smooth curve is the expected distribution. The abscissa is the number of intervals with the indicated value of χ^2.

to the observed χ^2 behavior.

5. Summary

The measurements included here, along with those in Harmon *et al.* (1991) and Finger *et al.* (1991) , clearly demonstrate that BATSE represents a considerable resource for near-continuous monitoring of moderately strong hard X-ray sources. This capability is a useful complement to the more sensitive OSSE pointed observations, and has already been used to advantage in the decision to alter the GRO viewing schedule to observe GX339-4.

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