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STATUS REPORT

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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TIMING ANALYSIS OF LOW-ENERGY GAMMA-RAY EMISSION FROM GALACTIC COMPACT OBJECTS USING THE GAMMA RAY OBSERVATORY

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Submitted by:

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ORIGINAL CONTAINS
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The principal goal of our Phase I investigation was the development of techniques and data analysis tools for pulsar searches and timing. After the launch of the *Compton Observatory* we received from the BATSE team one day of DISCLA data for use in the development and testing of data analysis techniques. Using this first day of data for testing and optimizing our timing tools we detected four X-ray binary pulsars, Vela X-1, Cen X-3, 4U 0115+63, and GX 301-2. Subsequently we received four more days of data, allowing us to test our timing tools with data from a variety of days. In summary, using the tools we developed based on the first day of data that we received, we have detected 8 pulsars in five days of data, or roughly one quarter of the approximately 30 known X-ray binary pulsars. In addition to the pulsars listed above we detected GX 1+4, 4U 1626-67, OAO 1657-415, and Her X-1. Many of the data analysis tools that we developed have been ported to MSFC and are being used for the analysis of BATSE data. This appendix describes some of the timing tools and presents *preliminary* pulse period and phase profile results. END

In order to facilitate exchange of tools and data between the BATSE team and the Caltech group we early-on committed to using the IDL environment for program development. IDL is an interactive data analysis and graphics programming environment that runs on readily accessible workstations and microcomputers. Thus when this section refers to analysis tools it generally implies an IDL routine or procedure to perform a data analysis task.

The unique character of all-sky monitoring and continuous time coverage results in the constraint that any effective tool for the detection of pulsars has to be relatively automatic due to the large quantity of data. This requirement drove the early development of tools to read the raw DISCLA data and housekeeping data, detect and correct or remove systematic problems, resulting in a data flow which could easily be piped into the timing analysis. The result of the timing analysis is a list of candidate periods and/or power spectra. Initially the detectors were analyzed singly. Subsequently they were analyzed singly, in pairs, and quads corresponding to the exposed combinations of detector areas to potential sources. In Figure B.1 we show a plot of BATSE LAD Discriminator data in the energy band 20-60keV. These data form the starting point of our analysis. The strong orbital modulation of the background, gaps, and unusual temporal features provide the challenge to looking for periodic signals from X-ray binary pulsars. The interesting signals from the pulsars are weak in comparison to the background fluctuations, accounting for count rates of only a few to tens of counts per second.

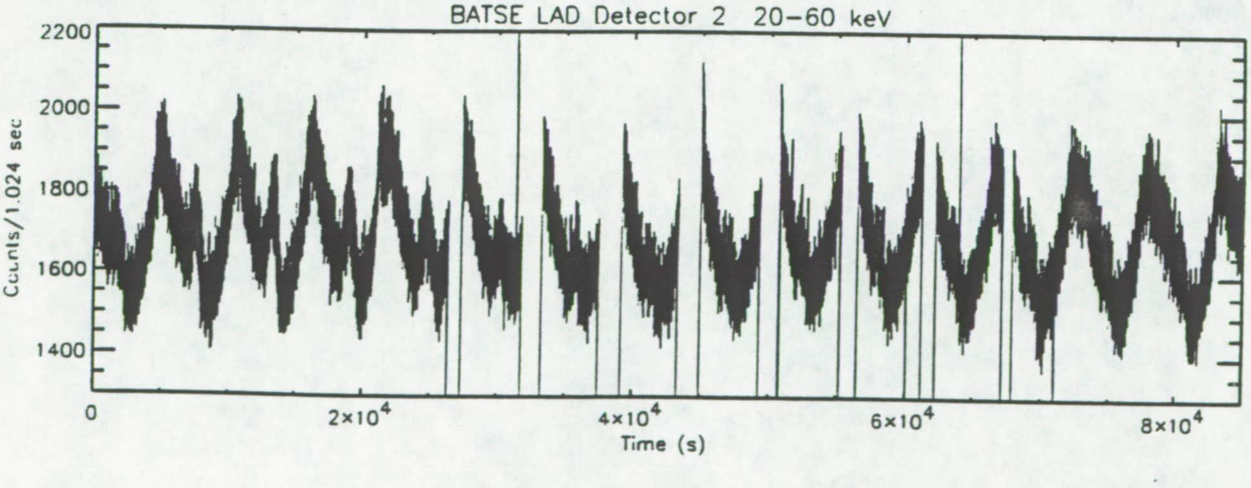


Figure B.1 BATSE LAD Detector discriminator data (DISCLA) to which is applied the signal processing for X-ray binary pulsar searches. A strong pulsar signal would contribute about 10 cts/1.024s in these data, small in comparison to the background variations.

The core of the timing analysis is based on a series of both time domain and frequency domain signal processing techniques designed to 'filter' out noise due to the orbital modulation of the background, occultation edges of bright steady sources, and other systematic effects. The goal is to produce a time series which has the large systematic effects removed without attenuating or significantly distorting the pulsar signals buried in the data. In Figure B.2 we present the filtered times series for the data which was presented in Figure B.1. Data of this quality forms the input for the power spectral techniques applied to the search for periodic signals from pulsars. Also note that this signal is now a zero mean time series, the dc component having been removed. Thus in this analysis only the pulsed flux can be determined.

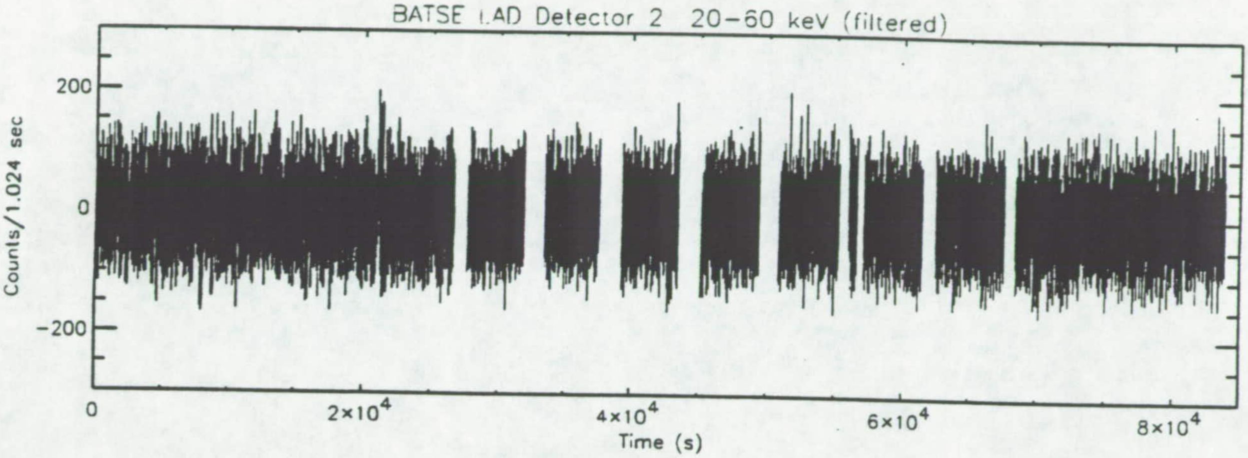


Figure B.2 Filtered time series produced from frequency domain and time domain signal processing on the data shown in Figure B.1. The data shown in this Figure is analyzed to obtain the power spectrum for the pulsar searches.

Additional effort went into the development of basic tools for efficient power spectrum generation and search/sorting tools to allow the automatic processing of data. It was this first generation of tools, working with the single detector combinations which led to the detection of the first group of pulsars.

Our next step was to utilize multiple detectors, weighted optimally for given directions in the sky. This provided both enhanced sensitivity and a means of testing whether a given signal is systematic or source-related. Using multiple-detector combinations, we were able to detect an additional source, GX1+4. At that time, GX1+4 was not yet in its recent high state. As an example, Figure B.3 shows the power spectral density in the region around the signal from Vela X-1 during a flare episode for the optimal combination of detectors for that source direction. This figure also shows the sidelobe structure introduced by occultation of the source by the earth, gaps, and the finite length of the observation.

During a visit to Marshall Space Flight Center in August, the initial software developed at Caltech was ported to the BATSE workstation environment. Analysis of 3 additional days of data, yielded two new detections: 4U 1626-67 and OAO 1657-415. We note that OAO 1657-415 was a target specifically identified in our Phase I proposal as a possible candidate for detection by the *Compton Observatory*.

In September and October, our work concentrated on an enhanced software package optimized for the particular directions and period ranges of known accreting pulsars. We also began to search for the "aliased signal" of several fast pulsars with periods shorter than the Nyquist-limit of 2.048 s. A combination of short transforms (~1 orbit) and optimization for aliased frequency yielded detection of Her X-1 on one of the 5 days of available data. Graphical techniques, allowing quick visual interpretation of a large number of power spectra, based on the short transforms, were developed during this period. An example of this technique is shown in Figure B.4 showing the detection of Her X-1, Vela X-1, and Cen X-3. This detection and frequency determination provided important information needed to detect Her X-1 in the BATSE on-board folded data mode.

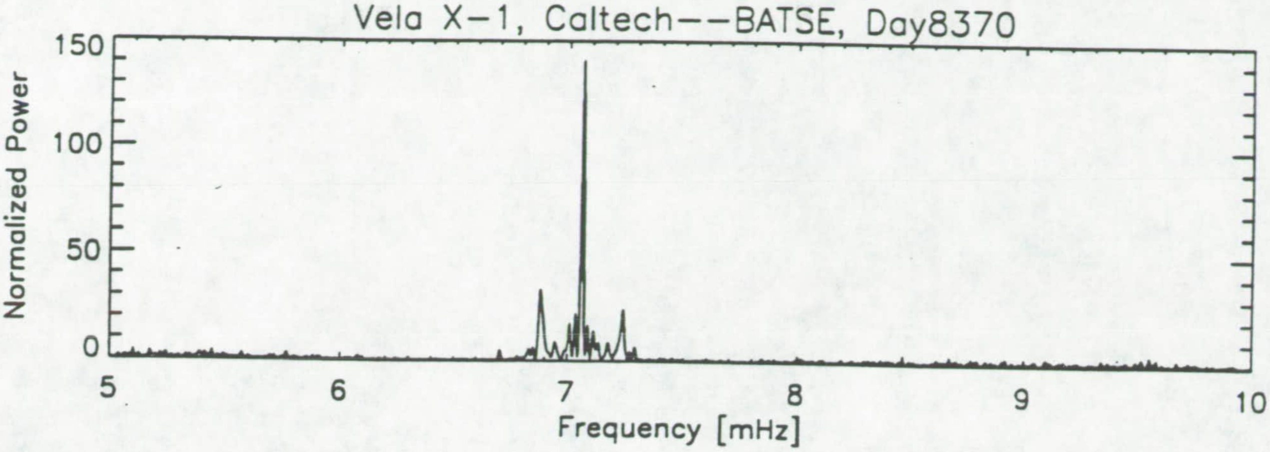


Figure B.3 Power spectrum derived from BATSE LAD discriminator data on JD=2448370 in the energy range 20-60keV. Only the region around the frequency corresponding to Vela X-1 is presented and shows the complicated sidelobe structure introduced from earth occultations.

Recently, we have developed tools for the following searches:

- **All-sky**, using the highest sensitivity detector combinations
- **Galactic plane**, using earth-occultation windowing and optimal detector combinations
- **Individual source**, (40 sources) using optimal combinations, windowing, and period-range restrictions

These are currently being applied to a two-week interval of BATSE data. We have also developed routines to perform solar system barycentering of time series for period determinations, tools to perform pulse folding, and have started to develop tools for the analysis of the pulsed flux.

Another area of signal processing which is currently under development uses acceleration and circular orbit searches. In our preliminary investigations we have shown that analysis of a BATSE time series containing Cen X-3, accelerated to take into account the pulsar motion about its companion, significantly increased the detection level of the source. This is not at all surprising given that the decoherence time for Cen X-3 in its tight binary orbit of 2.1 days is about 1.5 hours. We plan to use these techniques extensively for searches of known and new pulsars, and also to remove the sometimes large signals from known pulsars in order to search for weaker signals in the data. These acceleration techniques put the time series in the frame of the pulsar, which will also facilitate detailed timing studies of the objects. The biggest challenge for the blind searches is the large orbital-parameter phase space, combined with lack of directional knowledge for unknown pulsars. These are part of what will be addressed in our Phase II investigation.

Our investigation so far has concentrated on the Phase I objectives of technique and software development. Scientific investigations of accreting pulsars using BATSE are just beginning. Some very preliminary results were presented by the BATSE team at the GRO Science Workshop in September, and additional results will be discussed by both BATSE team members and Caltech investigators at the January AAS meeting.

In figures B.5 through B.9 we show preliminary observational results, giving an indication of the detections made to date. In Table B.1 we also present preliminary solar system barycentered periods for six of the pulsars we have detected with BATSE. Pulse profiles, pulse periods and period histories are fundamental tools for study of accretion powered pulsars. The preliminary results presented in this appendix, based on only five days of data, demonstrate the potential of the the tools that we have developed, and the power of the BATSE detectors for the study of these objects. We would like to stress that while we have only plotted a single period determination (or two in the case of GX301-2) in the Figures, these presentations only make use of a small fraction, generally only one day, of the BATSE data. Our techniques when applied to all of the BATSE observations will provide nearly *continuous* measurements of the pulse period for many of the steady sources.

We anticipate that this investigation will result in the detection of many more of the known X-ray binary pulsars, as well as previously undetected sources. In Table B.2 we present a list of candidates which we feel it is likely that we will detect in BATSE data using some of the techniques that we have developed and will be refining through Phase II.

TABLE B.1 X-Ray Binary Pulsar Periods

Source	TJD	Period [sec]
4U 0115+63	8370	$3.6143878 \pm 4.3 \times 10^{-6}$
4U 1626-67	8465	$7.661386 \pm 7.4 \times 10^{-5}$
OAO 1657-415	8482	37.697 ± 0.001
GX 1+4	8370	115.275 ± 0.020
Vela X-1	8370	283.215 ± 0.016
GX 301-2	8370	682.794 ± 0.245
GX 301-2	8465	679.558 ± 0.184

TABLE B.2

Candidates for Future BATSE Detection				
Name	P_{puls} (s)	P_{orb} (days)	Comments	References on Source Characteristics
SMC X-1	0.72	3.89	Sub-nyquist[a]	Gruber and Rothschild (1984)
V 0332+53	4.37	34.3	Recurrent, Be	Makishima et al. (1990)
LMC X-4	13.5	1.41	Short P_{orb}[b]	Levine et al. (1991)
EXO 2030+375	41.8	$\sim$46	Transient[c]	Parmer et al. (1989)
Cep X-4	66.3	$\geq$23	Transient	Mihara et al. (1991)
A0535+26	104	111	Bright, recurrent	Coe et al. (1990)
4U 1538-52	529	3.73	Long P_{puls}[d]	Clark et al. (1990)
X Per	835	580 ?	Recurrent, Oe[e]	Worrall et al. (1981)

[a] Possibly detectable in high state at 2nd alias; requires binary orbit search

[b] Almost certain to be detected using orbital parameter search

[c] Easily detectable in outburst; only one outburst observed to date

[d] Detectable with improved orbital background model

[e] Possibly detectable with improved orbital background model

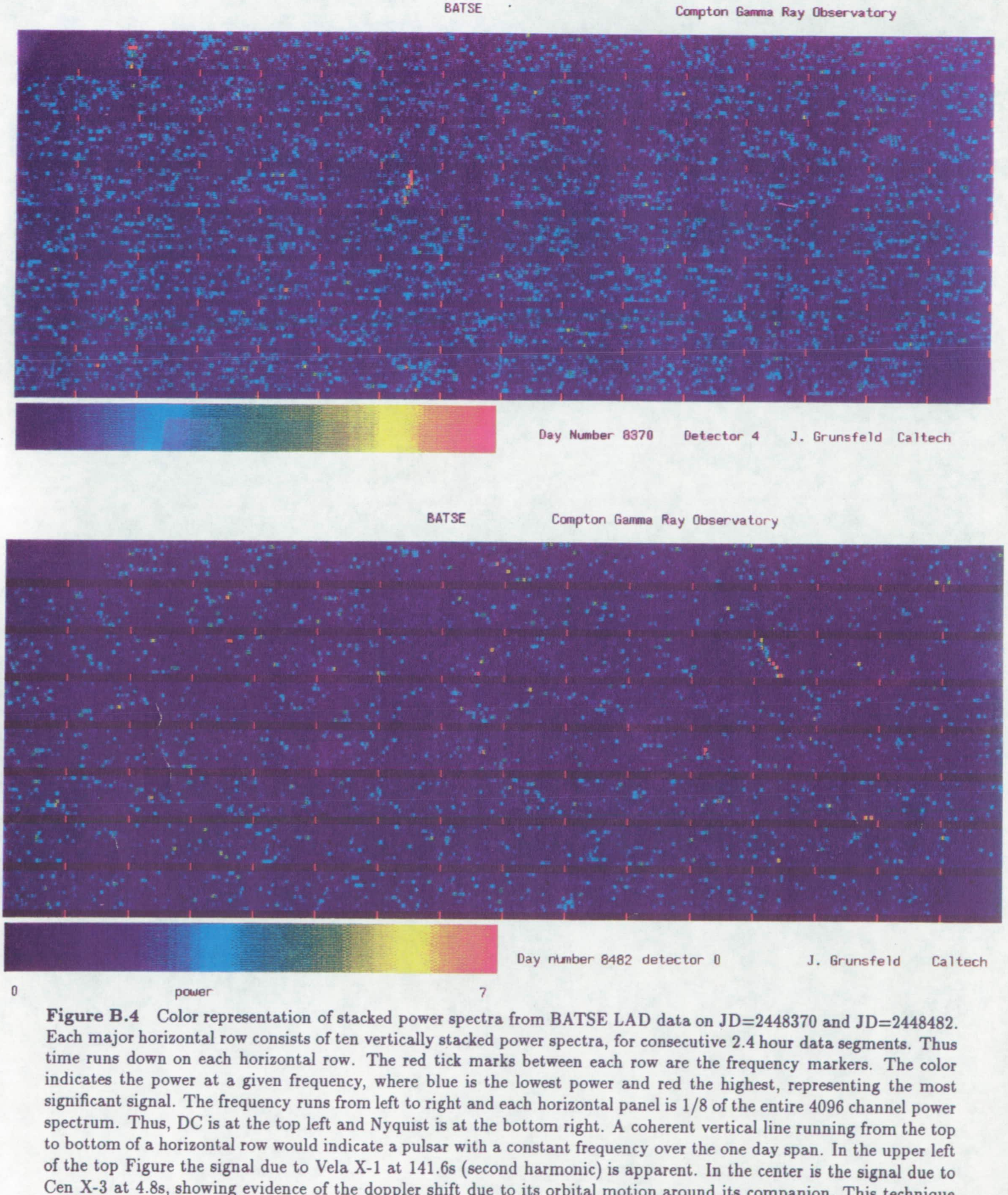
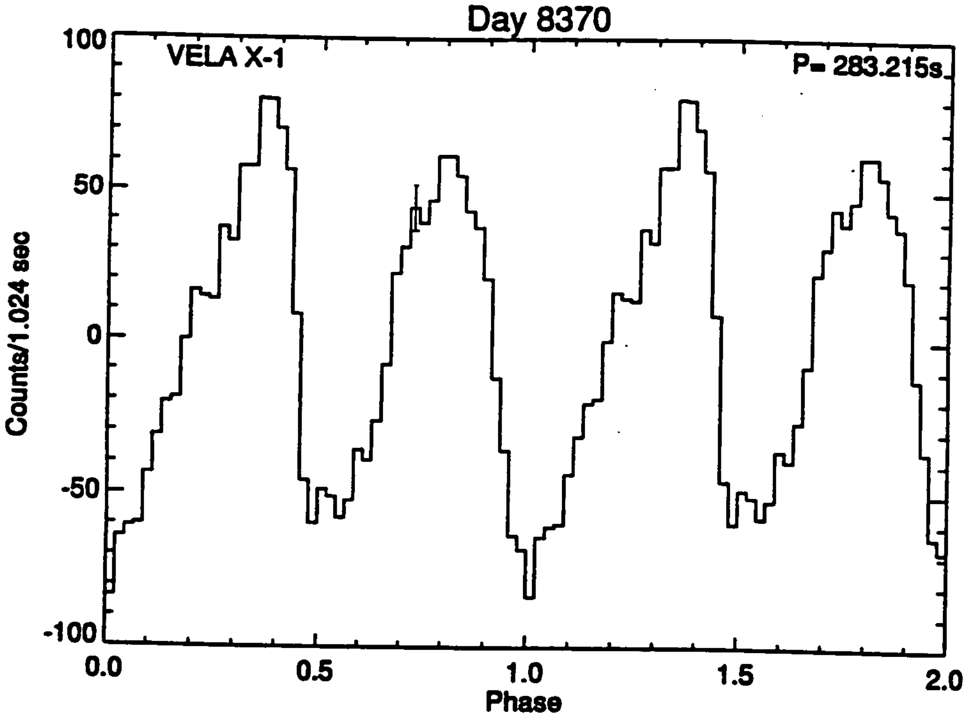


Figure B.4 Color representation of stacked power spectra from BATSE LAD data on JD=2448370 and JD=2448482. Each major horizontal row consists of ten vertically stacked power spectra, for consecutive 2.4 hour data segments. Thus time runs down on each horizontal row. The red tick marks between each row are the frequency markers. The color indicates the power at a given frequency, where blue is the lowest power and red the highest, representing the most significant signal. The frequency runs from left to right and each horizontal panel is 1/8 of the entire 4096 channel power spectrum. Thus, DC is at the top left and Nyquist is at the bottom right. A coherent vertical line running from the top to bottom of a horizontal row would indicate a pulsar with a constant frequency over the one day span. In the upper left of the top Figure the signal due to Vela X-1 at 141.6s (second harmonic) is apparent. In the center is the signal due to Cen X-3 at 4.8s, showing evidence of the doppler shift due to its orbital motion around its companion. This technique is very powerful for detecting pulsars with short orbital periods, as well as transient emission. The bottom Figure shows the power spectrum in which Her X-1 was detected on day number JD=2448482. Her X-1 has an orbital period of 1.7 days resulting in a significant shift in frequency over the one day span covered by this figure. This produces the slant to the track in the stacked power spectra.



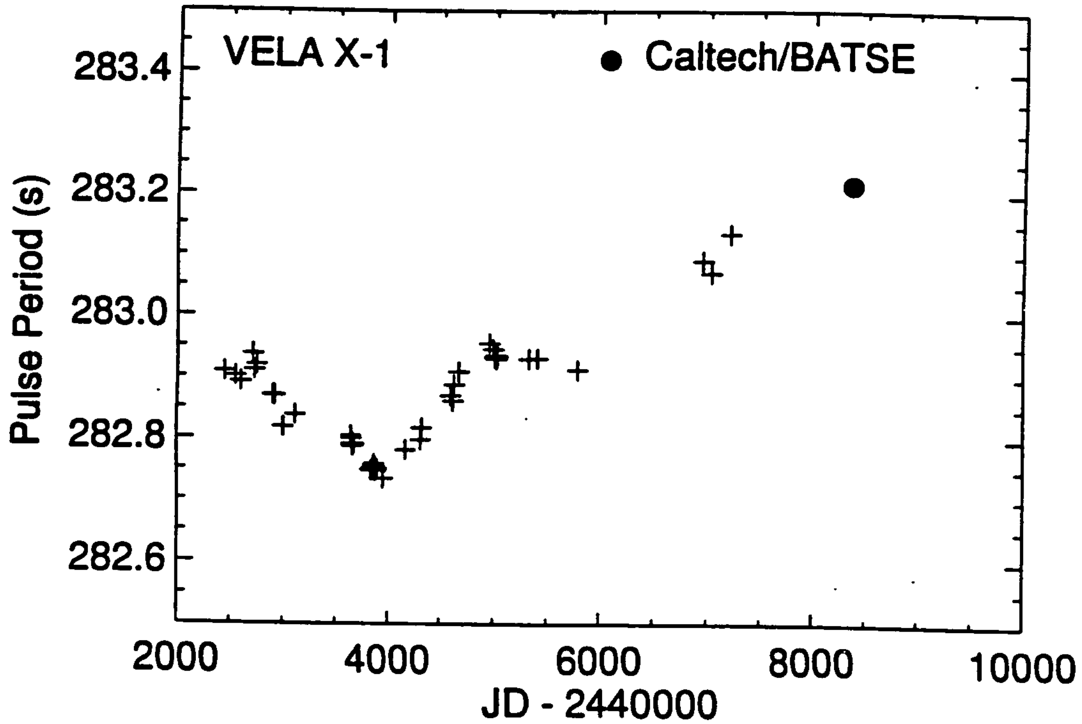


Figure B.5 Pulse profile and pulse period history for Vela X-1, including preliminary data derived from the Caltech Phase I investigation. The pulse period has been corrected to the solar system barycenter, but not to the pulsar frame.

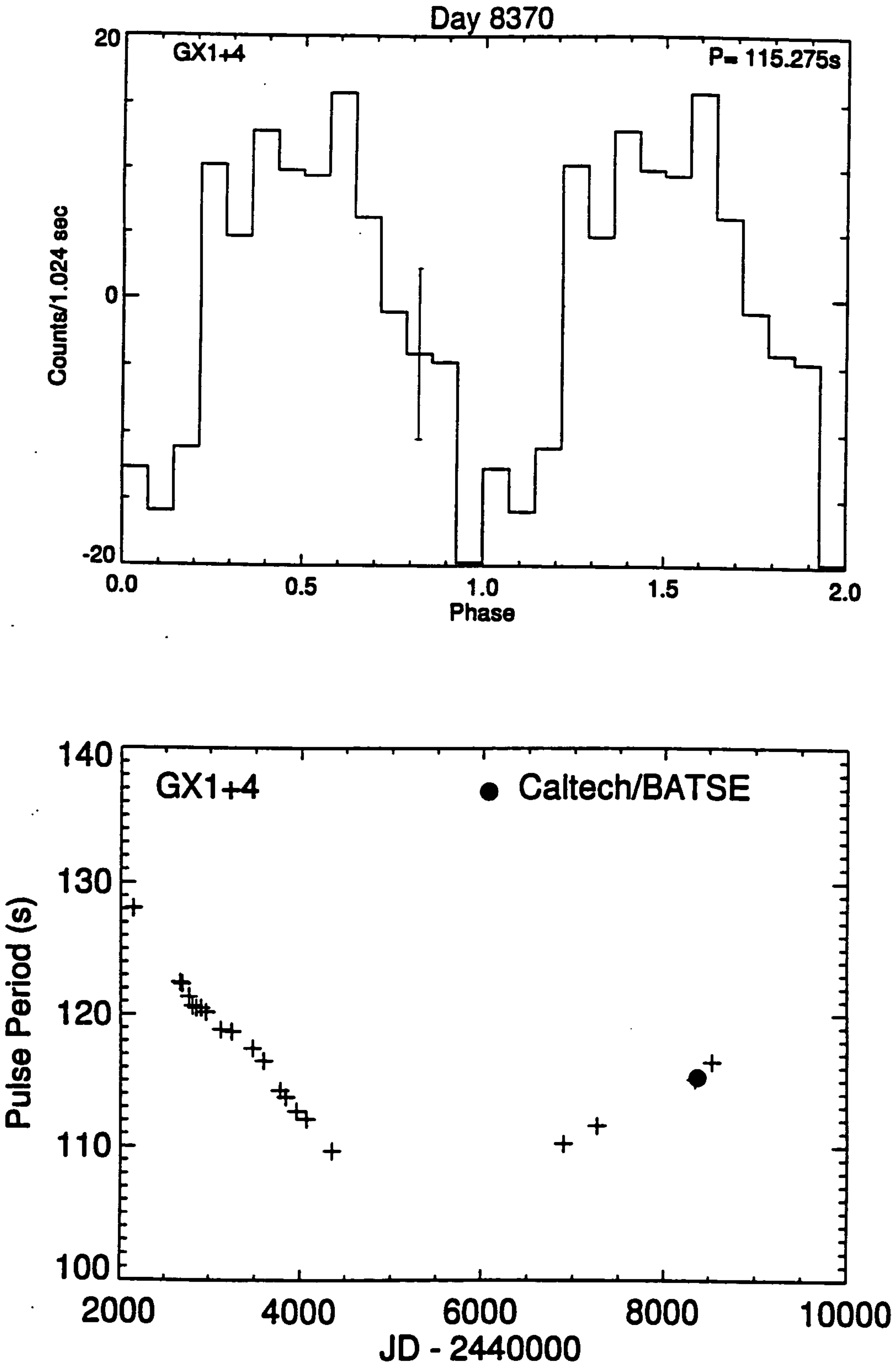
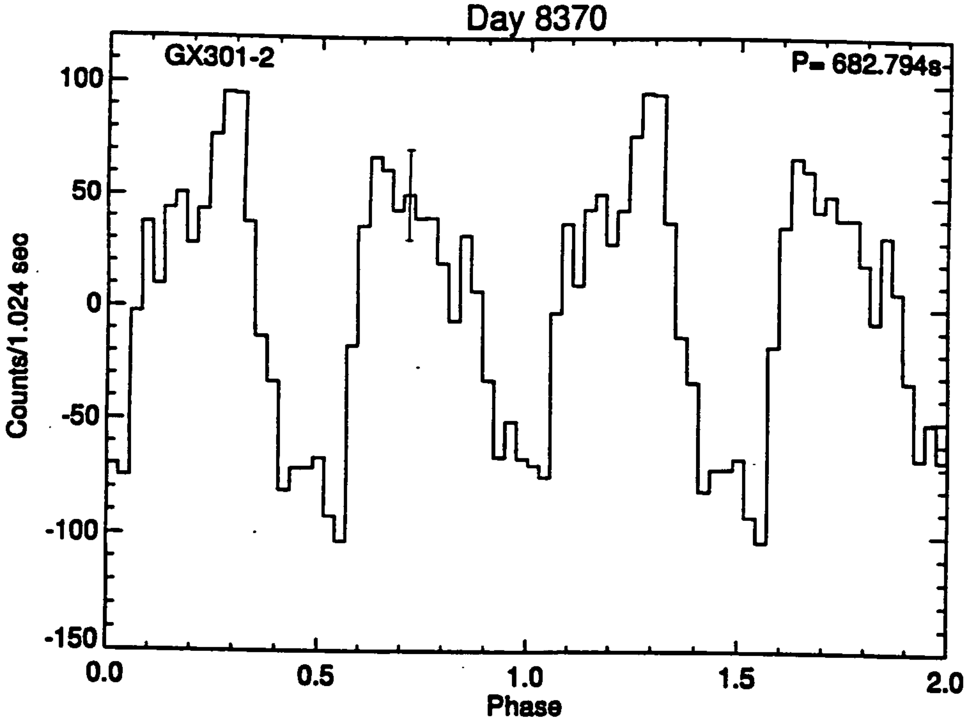


Figure B.6 Pulse profile and pulse period history for GX1+4, including preliminary data derived from the Caltech Phase I investigation. The pulse period has been corrected to the solar system barycenter, but not to the pulsar frame. Contemporary pulse period results from the GRANAT observatory are shown.



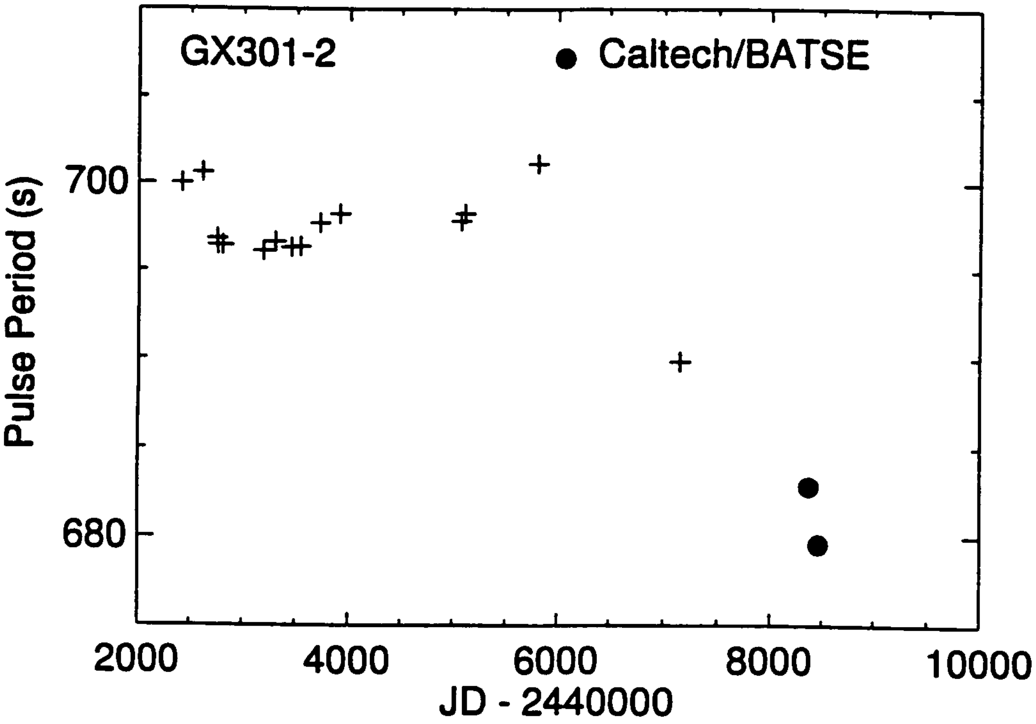


Figure B.7 Pulse profile and pulse period history for GX301-2, including preliminary data derived from the Caltech Phase I investigation. The pulse period has been corrected to the solar system barycenter, but not to the pulsar frame. The pulse period history shows the dramatic change in pulse period observed in the last few years in this wind fed system.

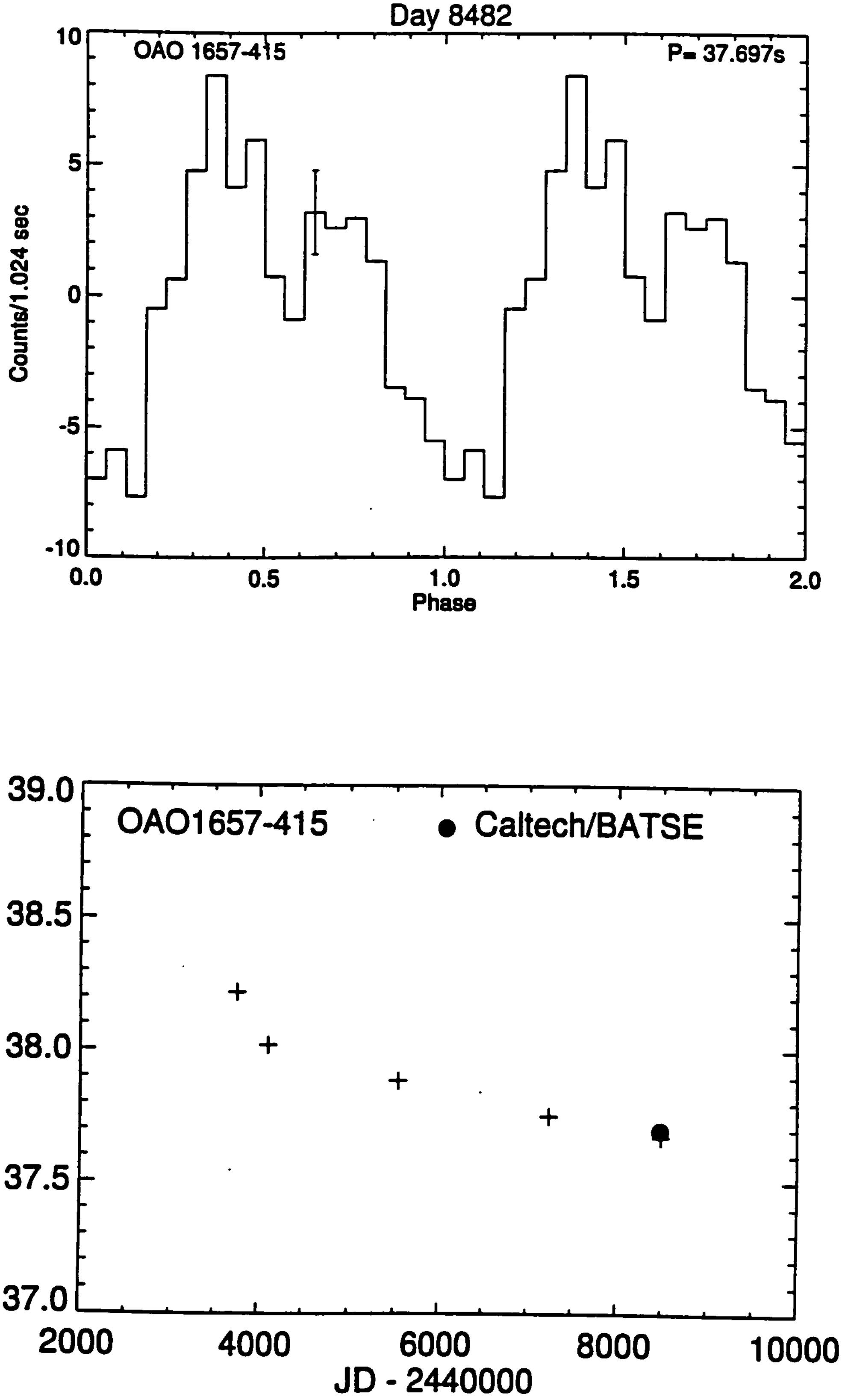


Figure B.8 Pulse profile and pulse period history for OAO 1657-415, including preliminary data derived from the Caltech Phase I investigation. The pulse period has been corrected to the solar system barycenter, but not to the pulsar frame. BATSE observations of this source, which has been only been observed by a few experiments, may well elucidate the nature of the accretion in the system, i.e. wind or disk accretion.

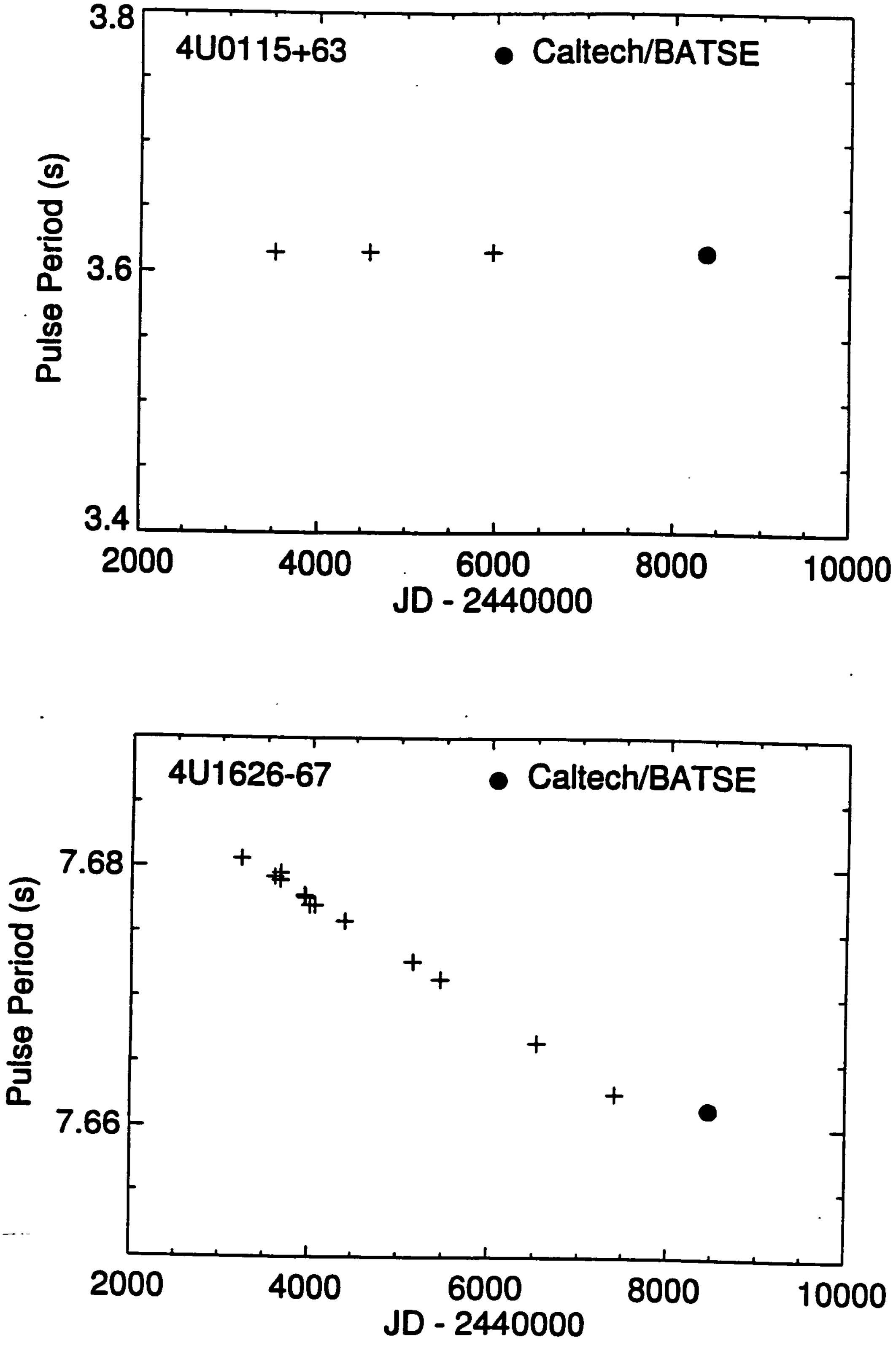


Figure B.9 Pulse period histories for 4U 0115+63 a Be/X-ray binary system, and 4U 1626-67, including preliminary data derived from the Caltech Phase I investigation. The pulse period has been corrected to the solar system barycenter, but not to the pulsar frame. While these results are preliminary the pulse period measured for 4U 1626-67 is intriguing due to its apparent deviation from the roughly linear trend observed by previous measurements.