Orbit Determination for the Be/X–Ray Transient EXO 2030+375

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Abstract. The Be/X–ray binary transient pulsar EXO 2030+375 has been observed during twenty–two outbursts over four years (1991–1994) using the large area detectors (LADs) of the Burst and Transient Source Experiment (BATSE) on the Compton Gamma–Ray Observatory (CGRO). Thirteen outbursts between 1992 February and 1993 August occurred regularly at ~46 day intervals, close to the orbital period determined using EXOSAT data (Parmar et al. 1989). EXOSAT discovered this pulsar during a "giant" outburst in 1985 May (Parmar et al. 1985). All BATSE outbursts were "normal" type. Pulse phases derived from the thirteen consecutive outbursts were fit to two different models to determine a binary orbit. A summary of the results are presented here.

INTRODUCTION

The Be/X–ray transient pulsar EXO 2030+375 was observed by BATSE during twenty–two outbursts from 1991 May to 1994 June. The flux history (20–50 keV) and spin frequency history for the source from the BATSE observations appear in Figures 1 and 2. The vertical dashed lines in both figures bracket thirteen outbursts that recurred at consecutive ~46 day intervals. Each of these outbursts lasted 7–15 days. Preliminary results for these data were presented in [3] and [4]. The epoch–folded pulse profile was double peaked and showed no significant variations either with flux or energy. One–day spectral fits over all thirteen outbursts were performed using an exponential model with a variable kT parameter. The weighted average kT value was found to be 20.2 ± 0.3 keV. Here we summarize results from a timing analysis of the 13 consecutive outbursts.

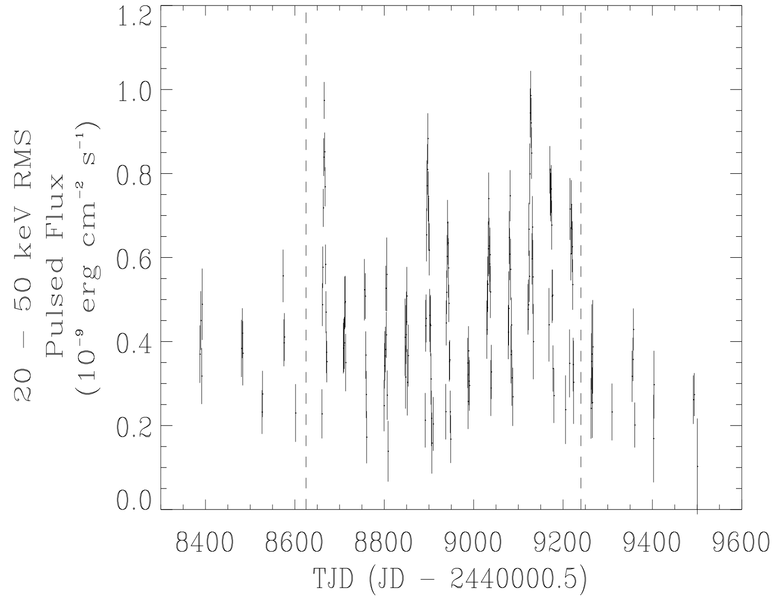

FIGURE 1. Flux history (20–50 keV) for EXO 2030+375 for the BATSE observations.

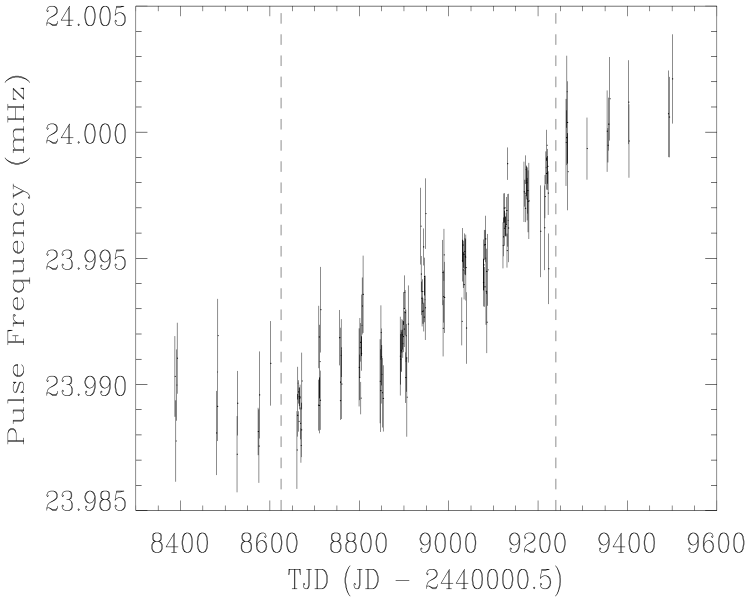

FIGURE 2. Spin frequency history for EXO 2030+375 for the BATSE observations.

PULSE TIMING

The spin frequencies at mid–outburst for the thirteen outbursts were linearly fit to obtain global values of ν and $\dot{\nu}$ for a preliminary phase model that was quadratic in t, the emission time of pulses from the pulsar. The BATSE DISCLA data (20–50 keV) were folded using this phase model and the orbital parameters from [4].

Phase offsets with respect to the preliminary ephemeris were obtained using a template matching procedure in Fourier space between the harmonic representation of the pulse profile for each folded single day of data and that of a scaled and shifted master template extracted from the first of the thirteen outbursts, Truncated Julian Days (TJDs) 8660–8672. The procedure was equivalent to a cross–correlation between the profile and the template [5] but allowed weighting of the harmonics by their errors. Monte Carlo simulations using the master template showed that this method could find accurate phase offsets down to a signal–to–noise ratio of 2.5 (defined here as the ratio of the daily pulsed flux value to its error) before substantial departures from the expected Gaussian distribution occurred. Therefore, a 2.5 signal–to–noise cutoff for the data was established and days with a lower value were discarded.

Cygnus X–1 was a source that contributed noise to the BATSE observations of EXO 2030+375. To account for the presence of this source, the ten Fourier harmonics used to construct the daily pulse profiles were identified in daily power spectra for EXO 2030+375 and the average power obtained for 21 mHz intervals centered on each harmonic. The errors for each harmonic were multiplied by the square root of the average Leahy normalized power divided by two.

Deeter [5] has suggested that retaining harmonics in the master template dominated by noise would degrade the pulse phase estimation. Therefore only the first 7 harmonics were retained. A comparison via a χ^2 minimization was performed between the first outburst template and three other templates drawn respectively from all of the outbursts, only the strong outbursts, and only the weak outbursts to determine if a better master template could be used. The lowest χ^2 value was obtained for the all–outburst template and so it was selected as the new master template.

The provisional phase model was corrected further by fitting a second degree polynomial to the total phase (phase model + phase offsets) for each outburst to obtain improved values of ν and $\dot{\nu}$. The DISCLA data were refolded using these corrections.

ORBIT FITTING

The orbit fit from [4] had an unacceptable reduced χ^2 of 3.39, leading us to try to improve the fit. As a first attempt, a polynomial was used to model the

TABLE 1. EXO 2030+375 Orbit Parameters from the Two Models.

Parameter	Polynomial Model	Gaussian Model
χ^2/dof	183.14/116	121.25/102
$P_{\rm orb}$	46.017 $\pm$ 0.003 days	46.01 $\pm$ 0.02 days
e	0.37 $\pm$ 0.02	0.37 $\pm$ 0.02
$a_{\rm x}$ sin i	257 $\pm$ 14	264 $\pm$ 21 lt-sec
ω	223.0 $\pm$ 1.9 degrees	223.4 $\pm$ 3.9 degrees
$T_{\rm p}$	JD 2448936.9 $\pm$ 0.2	JD 2448937.0 $\pm$ 0.3
$f(M)$	8.42 $\pm$ 1.34	9.12 $\pm$ 2.17 $M_\odot$
σ		3.98 $\pm$ 1.22 days

phase contribution from the pulsar for all thirteen outbursts. The model used the difference between the pulse emission times in the pulsar rest frame and a phase epoch T_0 near the middle of the data. The coefficients for each order of the polynomial were estimated and held constant over the fit. All of the orbit parameters which affect the delay between emission and arrival times were allowed to vary for each polynomial order. Phases could not be connected between outbursts because of long periods when no X–rays were seen, so non–integer cycle slips were determined in the fitting process. Goodness of fit was evaluated for each polynomial order using a χ^2 minimization. Beginning with polynomial order 3, fits were made for each succeeding order until order 15 was reached. Fits beyond order 15 proved unmanageable. The resulting χ^2 value and orbit parameters for the 15th order fit are presented in Table 1.

A second model was tried that concentrated the spin–up torque for each outburst during the times when hard X–ray flux was observed by BATSE. This torque model was of the form

$$\dot{\nu}(t) = \phi''(t) = \dot{\nu}_0 + \sum_{i=1}^{13} B_i e^{-(t-\tau_i)^2/2\sigma_i^2} \ . \tag{1}$$

$\dot{\nu}_0$ represented the torque between outbursts while the summation was a Gaussian contribution to the frequency derivative during each outburst with a peak time $\tau_{\rm i}$ and half–width $\sigma_{\rm i}$. A polynomial representation for $\dot{\nu}_0$ was tried but was found unnecessary. The $B_{\rm i}$ coefficients are a direct measure of the peak torque. Gaussian fits to the observed X–ray flux for each outburst determined preliminary values of $\tau_{\rm i}$ and showed that all of the $\sigma_{\rm i}$'s were consistent with a single half–width σ, which was fixed in the final fit. All of the $A_{\rm j}$'s, $B_{\rm i}$'s, $\tau_{\rm i}$'s, σ, as well as all orbit parameters were allowed to vary for the fit. The resulting χ^2 value, the orbit parameters, and the Gaussian half width from the fit are shown in Table 1. Figure 3 shows the derived torque model for all thirteen outbursts.

The error bars at each peak are those of the Gaussian amplitudes determined by the fit. The best fit solution shows spin–up occurring during each outburst and a slight spin–down occurring between outbursts. The mean peak spin–up

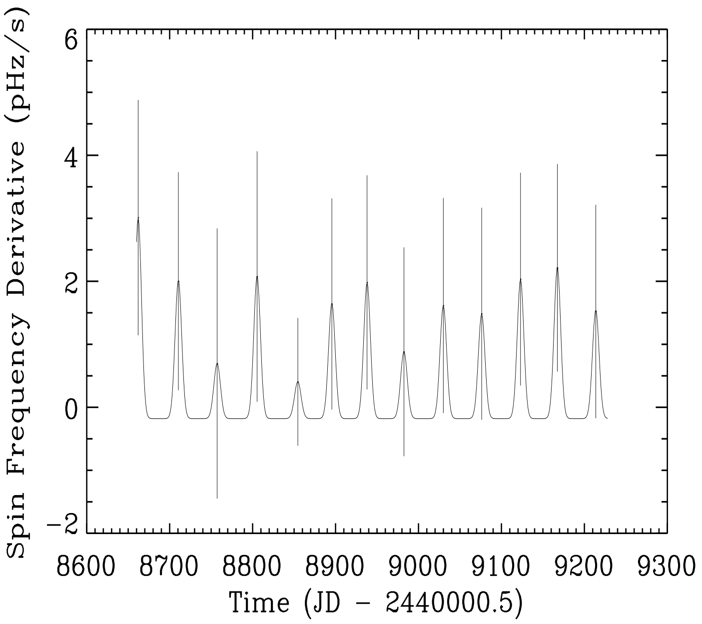

FIGURE 3. Torque values for EXO 2030+375 resulting from Gaussian orbit fit model. The uncertainties are highly correlated.

rate during outbursts above the inter–outburst level has a significance of only 1.1σ. Since this model does account for the physically expected behavior, the resulting orbital parameters and errors should be preferred to those from the polynomial model. A full presentation of this analysis is given in [6].

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