GRO J2058+42 X-Ray Observations

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Abstract. GRO J2058+42, a transient 198 second x-ray pulsar, was discovered by BATSE during a giant outburst in 1995 September-October. The total flux peaked at about 300 mCrab (20-50 keV) as measured by Earth occultation. The pulse period decreased from 198 s to 196 s during the 46-day outburst. BATSE has observed five additional weak outbursts from GRO J2058+42 with peak pulsed fluxes of about 15 mCrab (20-50 keV) that were spaced by about 110 days. The periodicity of the outbursts allowed a ToO observation by the *Rossi X-ray Timing Explorer (RXTE)* Proportional Counter Array (PCA) which localized the source to a $4'$ error circle. We present pulse frequency history, flux histories from pulsed and Earth occultation data, and representative pulse profiles.

INTRODUCTION

A periodic signal at about 198 seconds was observed in the BATSE data starting on 14 September, 1995. At the same time a new source was brightening in the Earth Occultation data. A location (figure 1) was determined from the pulsed data and the non-pulsed data with an error box of about $4^\circ \times 1^\circ$ [1]. A *CGRO* target of opportunity was declared and the spacecraft was re-oriented to allow scans of the region by OSSE. The error box (figure 1) was improved to $30' \times 60'$ [2]. The total flux (figure 2) peaked at about 300 mCrab (20-100 keV) and the pulsed flux (figure 2) peaked at 140 mCrab (20-50keV) on 27 September 1995. The bright outburst continued until 30 October 1995. A search of archival BATSE data from April 1991 until the bright outburst showed no previous outbursts.

An analysis of data following the bright outburst initially revealed three much weaker outbursts lasting about two weeks with pulsed fluxes peaking at 10-15 mCrab (20-50 keV). These outbursts were spaced by about 110 days (figure 2). From this regular spacing, the peak of the next outburst was predicted to be on November 28, 1996. A public target of opportunity scan of

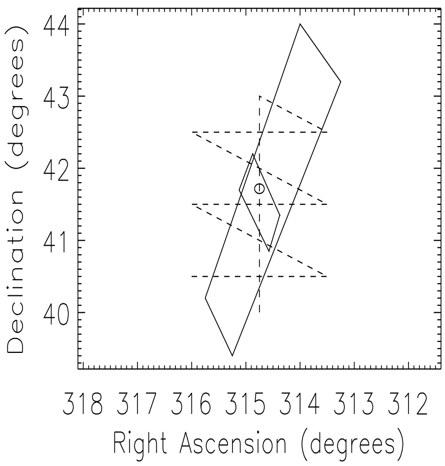

FIGURE 1. History of localization of GRO J2058+42. The large error box was determined from BATSE pulsed and non-pulsed data [1]. An OSSE scan of the BATSE error box yielded the smaller error box [2]. The *RXTE* PCA scan followed the path shown by the dashed line. The final location by *RXTE*, a $4'$ error circle, is shown by the small circle [3].

the error box was performed on November 28 with the *RXTE* PCA yielding a 90% confidence $4'$ error circle (figure 1) centered on (J2000) R.A. = $20^h\ 59^m.0$, Decl. = $+41°43'$ [3]. (See Wilson et al. in preparation for a description of the PCA observation.) BATSE was also detecting the source from November 23-December 1, 1996. An additional outburst was detected by BATSE about 110 days later (March 16-20, 1997). An archival search of *ROSAT* data found no sources within the error circle (J. Greiner, 1997, private communication). No optical counterpart has been found to date.

OBSERVATIONS

Figure 2 shows histories of spin frequency, pulsed intensity, and total (pulsed +unpulsed) flux determined at 4-day intervals. Pulse profiles were determined from the BATSE 20-50 keV DISCLA (1.024 second) data for a range of trial frequencies to search for a signal from GRO J2058+42. To generate each profile, the data are fit with a background model plus a sixth order Fourier expansion in pulse phase model for short intervals. In each four day span, the pulse profiles from the short intervals are shifted in phase and summed for a range of trial frequency offsets from the pulse phase model. The best fit frequency is determined by the Z_6^2 test which measures the significance of the first 6 Fourier amplitudes. For GRO J2058+42, root-mean-square (RMS) pulsed fluxes are estimated from the best fit pulse profile as $F_{RMS} = \left[\int_0^1 (F(\phi) - \bar{F})^2 d\phi\right]^{1/2}$ where $F(\phi)$ is the flux of the pulse profile at phase ϕ, $0 \leq \phi \leq 1$, and

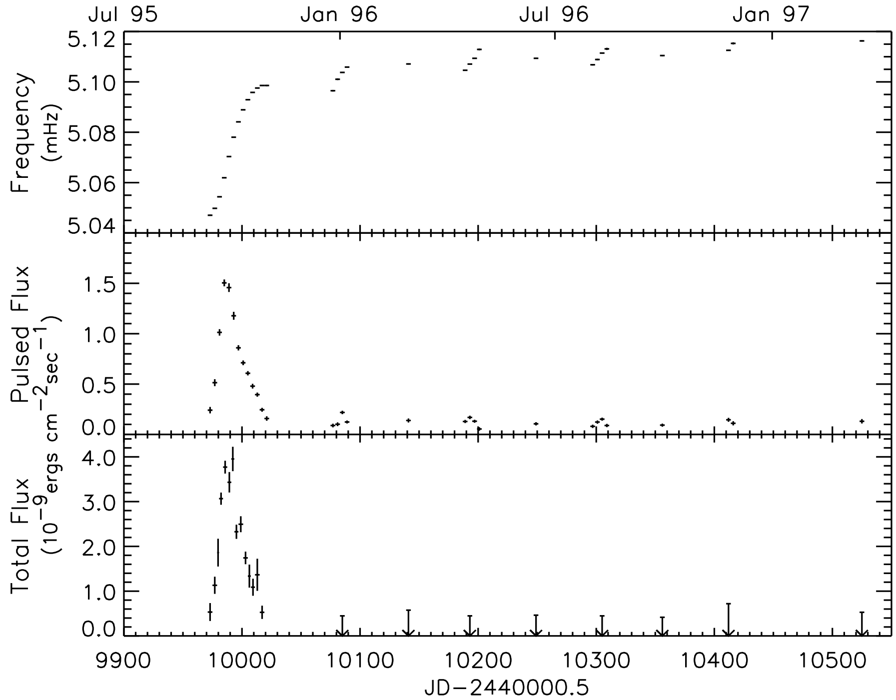

FIGURE 2. GRO J2058+42 frequency, pulsed flux (20-50 keV), and total flux (20-50 keV) determined at 4-day intervals. The spin frequencies have been barycentered, but have not been orbitally corrected since the orbit is unknown. Upper limits (3σ) are shown only for the peak total flux of the weak outbursts.

$\bar{F} = \int_0^1 F(\phi)d\phi$ is the average flux.The pulsed fluxes in the center panel of figure 2 were determined at 4-day intervals, assuming an exponential spectrum with an e-folding energy of 20 keV. See [4] for a detailed description of the pulse frequency and pulsed flux estimation techniques. The bottom panel of figure 2 shows the total 20-50 keV flux as measured by BATSE Earth occultation. The Earth occultation method measures the intensity of a known source by calculating the difference in total count rate in source facing detectors just before and just after source occultation by the Earth. This method measures the total flux from a source, including pulsed and unpulsed components [5]. The fluxes were determined at 4-day intervals by fitting count rates with an assumed exponential spectrum with an e-folding energy of 20 keV. Upper limits (3σ) for 4-day sums are shown for the peak fluxes of the weak outbursts.

GRO J2058+42 experienced a large spin up during its initial 46 day outburst (figure 2). The pulse period changed by about 2 seconds across this outburst, corresponding to an average $P/\dot{P}$ of 12 years. Measurements of the spin-up rate give a peak value of $2.48 \pm .02 \times 10^{-11}$ Hz s^{-1} (not orbitally corrected) which is comparable to peak spin-up rates seen by BATSE in giant outbursts from known Be transients [4]. The large spin-up rate and brightness of this outburst compared to later outbursts leads us to classify the initial outburst from GRO J2058+42 as a giant outburst [6]. The bright initial outburst is followed by a series of much weaker outbursts, too dim to be unambiguously detected in Earth occultation data. The weak outbursts appear to alternate in duration and intensity (figure 2), producing brighter outbursts every 110 days with dimmer outbursts halfway between. The All-Sky Monitor (ASM) on the *RXTE* shows outbursts of approximately equal intensity and duration every 55 days [7]. No known systematic effects would remove or weaken outbursts in the BATSE data at 55 day intervals. However, the ASM measures total (pulsed+unpulsed) flux, while the BATSE measurements are of pulsed flux only, hence energy dependent changes in pulse fraction could cause the observed differences. See Wilson et al. in preparation for a full description of BATSE and ASM observations.

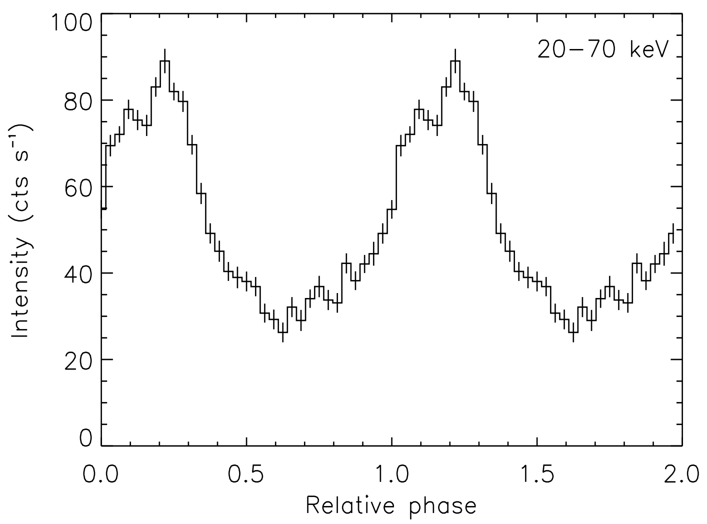

FIGURE 3. A pulse profile for 20-70 keV from September 23-27, 1995, near the peak of the giant outburst. The average count rate from occultation data for September 23-27,1995 has been added to the count rate plotted, but has not been included in the errors.

Pulse profiles for four energy bands, 20-30, 30-40, 40-50, and 50-70 keV were generated by epoch-folding four day intervals of BATSE CONT (2.048 second) data into 32 phase bins using a quadratic phase model, with no orbital model. Figure 3 shows a pulse profile for 20-70 keV from near the peak of the giant outburst of GRO J2058+42. Epoch-folded subsets of the September 23-27 interval also show a dip at phase ≈ 0.15, just preceding the peak of the profile emission. Our analysis has revealed preliminary evidence for profile variations during the giant outburst (See Wilson et al. in preparation for details). The pulse fraction appears to be constant across the giant outburst. An exponential photon spectrum was well fit to the total flux as measured by earth occultation and the pulsed flux, with consistent best fit e-folding energies of 15-22 keV. No spectral trends with intensity were seen in the BATSE data from the giant outburst.

DISCUSSION

Long term studies of Be/X-ray binaries have demonstrated that giant outbursts followed by or intermixed with a series of periodic normal outbursts appear to be typical behavior for Be/X-ray binaries [4]. GRO J2058+42 is most likely a Be/X-ray pulsar because it exhibits transient outbursts recurring with presumably an orbital period of 110 days and it has both giant and normal outbursts. The odd-even effects in the intensity of the normal (weak) outbursts seen by BATSE suggest that we are seeing two outbursts per 110 day orbit. An inclined neutron star orbit out of the equatorial plane of the companion, which could produce two outbursts per orbit, has often been suggested as a mechanism for outbursts in Be/X-ray transients [8] . However, two outbursts per orbit have not been seen in other Be transients to date.

A Corbet diagram shows the spin period of accreting neutron stars versus the binary orbital period [9], [10]. On this diagram, the spin-periods of the Be transients are strongly correlated with their orbital periods. Two other types of systems, neutrons stars orbiting Roche lobe filling supergiants and neutron stars orbiting underfilled Roche lobe supergiants, fall into regions on the diagram. An orbital period of 110 days places GRO J2058+42 along the orbital period vs. spin period correlation for Be/X-ray binaries.

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