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LONG-TERM MONITORING OF THE ACCRETING PULSAR GX 1+4

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ABSTRACT

We present preliminary results from two years of *GRO*/BATSE hard X-ray (20–100 keV) monitoring of the $\sim$ 120 s accretion-powered pulsar GX 1+4. Daily pulse frequency measurements from 1991 April to 1993 September show an average spin-down of $\dot{f} \approx -5 \times 10^{-12}$ s^{-2}, with increases in the spin-down rate during high-luminosity intervals. The 20–100 keV pulsed flux spectrum for the interval TJD 8393–8406 is fit by a power-law index of 2.56 ± 0.04. Optical spectroscopy of the suggested red giant companion V2116 Oph taken during the 1993 September X-ray outburst from GX 1+4 show considerably strengthened emission line features, supporting the association.

1. INTRODUCTION

The accreting binary pulsar GX 1+4 was first discovered in a hard X-ray balloon observation over twenty years ago (Lewin, Ricker, & McClintock 1971). Glass & Feast (1973) tentatively identified GX 1+4 with the bright infrared source V2116 Oph. This association was strengthened by optical spectroscopy showing that V2116 Oph, an M6 III giant, is apparently in a symbiotic binary with a compact companion (Davidsen, Malina, & Bowyer 1977). Later refinements of the X-ray position ($\sim 30''$) remained consistent with this identification. During the 1970s, the X-ray source was in a high-luminosity state ($\sim$ 50–200 mCrab) and was observed to spin-up at a mean rate $\dot{f} \approx 6 \times 10^{-12}$ s^{-2}. In the early 1980s, GX 1+4 entered an extended low-state, with no significant soft X-ray flux detected down to a level of $\sim$ 0.5 mCrab (Hall & Davelaar 1983; Makishima et al. 1988). The source reappeared in a low-luminosity ($\sim$ 2 mCrab) *spin-down* state in 1987 (Makishima et al. 1988; Greenhill et al. 1989) and has continued to spin-down steadily at a mean rate ($\dot{f} \approx -5 \times 10^{-12}$ s^{-2}) which is very close to the former spin-up rate in magnitude.

This paper reports on the results of nearly continuous montitoring of GX 1+4 from 1991 April to 1993 September using the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* (*GRO*).

2. OBSERVATIONS AND RESULTS

BATSE consists of eight identical uncollimated detector modules arranged on the corners of the *GRO* spacecraft, providing an all-sky monitor of hard X-ray and γ-ray flux (Fishman et al. 1989).

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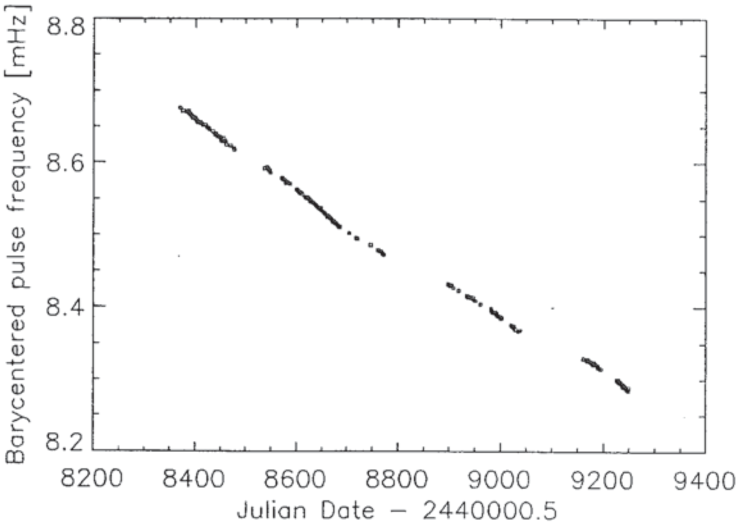

Figure 1: Spin frequency history for GX 1+4 derived from 20–60 keV BATSE data in the interval from 1991 April to 1993 September. Only data for which a significant signal was detected are shown.

We are reporting on observations from the BATSE large-area detectors (LADs), containing a NaI(Tl) scintillation crystal 1.27 cm thick and 50.8 cm in diameter and having an effective energy range of 20 keV–1.8 MeV. Our analysis makes use of two of the standard data types generated from the LADs. The DISCLA data, containing the photon count rate from each of the LAD discriminators in four energy channels at 1.024 s resolution, were used for timing studies. The CONT data, containing the LAD discriminator count rates in sixteen energy channels at 2.048 s resolution, were used for spectral studies.

Both data sets required extensive conditioning to remove the variable background effects caused by the spacecraft orbit. The DISCLA data were processed using an ad hoc model for the variable background (see Chakrabarty et al. 1993a for details), while the CONT data were processed using the more sophisticated background model developed by Rubin et al. (1993). Both approaches seek to reduce the data to a zero-mean time series, governed approximately by Poisson statistics. The time series for each day of the mission from the four detectors viewing GX 1+4 were then optimally weighted, summed, and barycentered to provide a BATSE observation of GX 1+4 for that day.

The results of daily GX 1+4 pulse frequency measurements (obtained by a Fourier transform search of the optimized time series described above) for data in the 20–60 keV range are given in Figure 1. The mean spin-down observed during this interval is $\dot{f} = -5 \times 10^{-12}$ s^{-2}, but the $\dot{f}$ averaged over intervals of weeks shows changes correlated with the pulsed flux. GX 1+4 undergoes intervals of bright flaring in its hard X-ray flux (see Figure 2), and during these bright periods the period history clearly deviates from the mean spin-down rate. However, the long-term mean remains remarkably stable.

Correcting for the instrument response, we have estimated a medium-resolution spectrum of the pulsed emission during the interval TJD 8393–8406, shown in Figure 3. The observed spectrum in the 20–100 keV range can be fit by a power-law of the form $dn/dE = C_{30}(E/30\mathrm{keV})^{-\alpha}$ with $\alpha = 2.56 \pm 0.04$ and $C_{30} = (3.0 \pm 0.1) \times 10^{-4}$ ph cm^{-2} s^{-1} keV^{-1}.

3. DISCUSSION

It has long been clear that torque reversals such as those observed in GX 1+4 (see Figure 4)

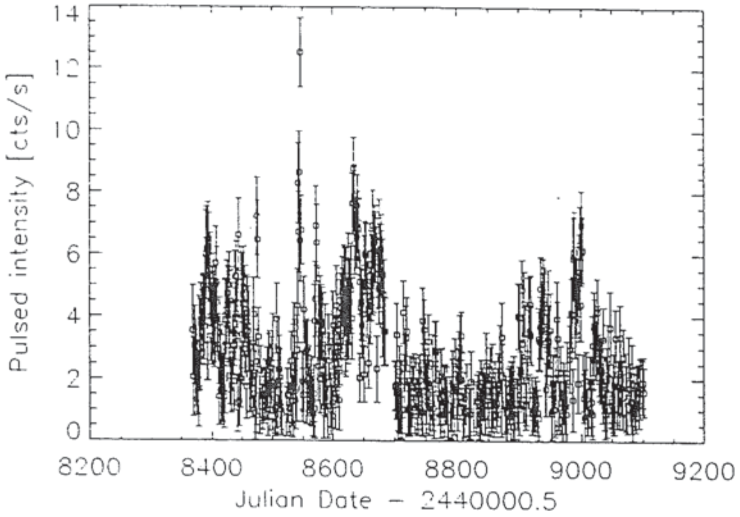

Figure 2: Pulsed flux history of GX 1+4 from BATSE data.

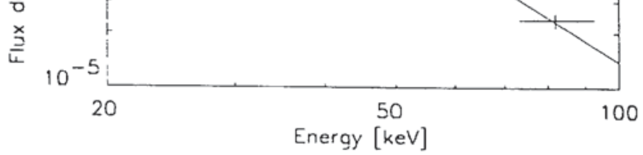

Figure 3: Pulsed flux spectrum for GX 1+4 on TJD 8634. The spectrum was fit to a power-law of the form $dn/dE = C_{30}(E/30\text{keV})^{-\alpha}$ with $\alpha = 2.56 \pm 0.04$ and $C_{30} = (3.0 \pm 0.1) \times 10^{-4}$ ph cm^{-2} s^{-1} keV^{-1}.

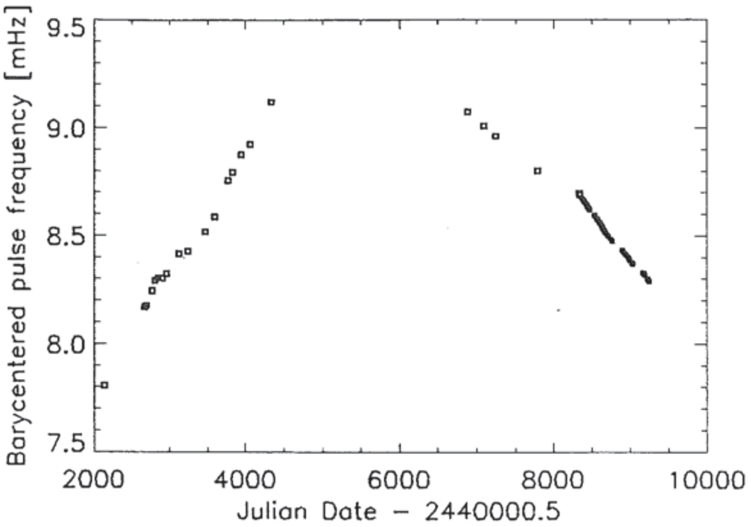

Figure 4: Long-term pulse frequency history for GX 1+4. The nearly solid curve starting at TJD 8370 contains the BATSE observations. There were no significant pulsed flux detections during the extended low state (TJD 4500–6500).

and more recently in 4U 1626-67 (Bildsten et al. 1993) must occur, given the brevity of the spin-up timescale ($|f/\dot{f}| \approx 30$ yr for GX 1+4) compared to the evolutionary lifetime ($\sim 10^6$ yr). The observations provide some information on the timescale for the reversals, but the detailed mechanism for them is poorly understood. Makishima et al. (1988) suggested that, in the case of GX 1+4, the change to spin-down might be due to the formation of a retrograde accretion disk from the slow, dense wind of V2116 Oph. Alternatively, we may interpret the spin-down as due to the pulsar being near its equilibrium spin period, in which case the Alfven radius and the corotation radius are nearly equal (Ghosh & Lamb 1979). For GX 1+4, this would imply a strong surface magnetic field ($B \sim 10^{14}$ G). The observed spin-down rate implies a torque value $N_{obs} = 2\pi I\dot{f} = 3.5 \times 10^{34}$ g cm^2 s^{-2}, where we have assumed that the neutron star has mass $M_x = 1.4 M_{\odot}$, radius $R_x = 10$ km, and moment of inertia $I = (2/5) M_x R_x^2$.

The suggested companion, V2116 Oph, remains unconfirmed although it is consistent with all of the X-ray position measurements. Optical spectroscopy taken during the 1993 September ($\sim$ TJD 9230) flare period (Finger et al. 1993) shows that the emission-line spectrum of V2116 Oph had grown much stronger than it had been prior to the X-ray outburst (Chakrabarty et al. 1993b), further supporting the association. From the observed infrared colors of V2116 Oph (Glass 1979), the interstellar extinction towards the source ($A_v \approx 6.5$), we can estimate the radius of the red giant companion,

$$R_c \approx 100 R_{\odot} \left(\frac{d}{4.2\mathrm{kpc}}\right) \left(\frac{T_{eff}}{3200\mathrm{K}}\right)^2 .$$

If we assume that companion is no larger than its Roche lobe, then we can calculate a lower limit on the orbital period as a function of the companion mass. Assuming co-rotation for the companion, Eggleton (1983) has given an approximate relationship between the Roche lobe radius, orbital separation, and mass ratio of a binary system,

$$\frac{R_L}{a} \approx \frac{0.49 q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})},$$

where $q = M_c/M_x$. Taking $R_L \approx R_C$ and $M_x = 1.4 M_{\odot}$, we can constrain the orbital period as

$$P_{orb} \gtrsim \left[\frac{4\pi^2 a_{min}^3}{G(M_x + M_c)}\right]^{1/2} .$$

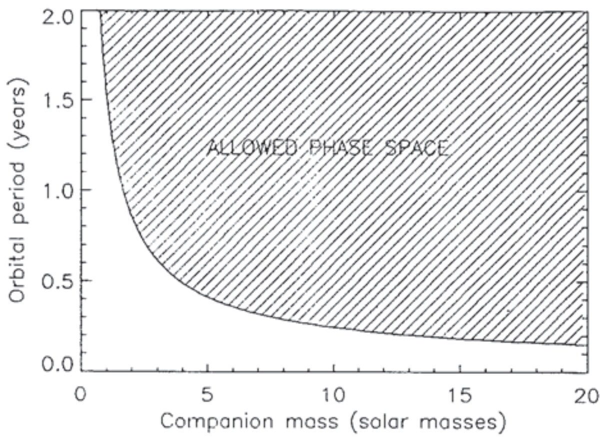

Figure 5: Constraints on the minimum allowed orbital period of GX 1+4 as a function of the mass of V2116 Oph, assuming $M_x = 1.4 M_\odot$ and that the system lies at a distance of 4.5 kpc, where the red giant has a radius of $100 R_\odot$.

For the expected range of red giant masses, the minimum orbital period is on a scale of years (Figure 5). An arrival time analysis of the BATSE data to search for orbital modulation of the pulsed emission is in progress.

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