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SEARCH FOR MILLISECOND X-RAY PULSATIONS FROM THE GALACTIC BULGE X-RAY SOURCE GX 9+1

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ABSTRACT

The recent discoveries of millisecond radio pulsars with small period derivatives and quasi-periodic oscillations in bright Galactic X-ray sources have given rise to theories which predict that low-mass X-ray binaries should have low-amplitude X-ray pulsations with short, possibly millisecond, periods. Most previous searches for these pulsations suffer from one or more of the following deficiencies: very short periods are not searched; the searches are not sufficiently sensitive; Doppler smearing of the pulsar due to its binary motion is ignored.

A 2.5 hr uninterrupted observation of GX 9+1 with 0.25 ms time resolution was obtained on 1985 September 21 with the Medium Energy Experiment on board the *EXOSAT Observatory*. We have used an optimum Coherence Recovery Technique to correct the data for Doppler smearing. A complete search covering the phase space of all likely binary orbits was performed on a Connection Machine CM-2, a data parallel computer well-suited for tasks of this type.

The complete search covered pulse periods between 0.5 ms and 17 min, binary periods greater than 3.6 hr, and companion star masses less than 0.9 $M_\odot$. Approximately 3000 independent orbits were searched in each of nine independent data segments; more than 5×10^9 spectral channels were examined. We obtain a 3 σ upper limit to the pulse fraction of GX 9+1 of 0.011 for periods greater than 1 ms, and 0.016 for periods between 0.5–1 ms.

Subject headings: pulsars — stars: individual (GX 9+1) — X-rays: binaries

I. INTRODUCTION

The bright Galactic bulge X-ray source GX 9+1 (=X1758−205) is a low-mass X-ray binary (LMXB; Langmeier *et al.* 1985). As such, it contains a neutron star accreting material from a Roche-lobe filling, low-mass stellar companion (Lewin and Joss 1983). If the neutron star is magnetized and spinning, then it should emit coherent X-ray pulsations. Pulsations with periods ranging from a few seconds to a few minutes have been detected in only a few of the more than 50 known LMXBs. Searches for X-ray pulsations from the brightest LMXBs, including globular cluster X-ray sources (Leahy *et al.* 1983), X-ray bursters (Cominsky *et al.* 1980), and bright Galactic bulge X-ray sources (Parsignault and Grindlay 1978; Spada, Rappoport, and Li 1983) have yielded only upper limits to the pulse fraction of greater than 4% for periods longer than 1 s. The lack of pulsations was taken as an indication that the surface magnetic fields of the neutron star primaries in LMXBs had decayed away (Lewin and Joss 1983).

Recent observational results and theoretical considerations have rekindled interest in periodic pulsations from LMXBs. Millisecond radio pulsars, first discovered in 1983, are thought to have evolved from LMXBs in which the mass transfer powering the X-radiation spins the neutron star up to millisecond periods through angular-momentum transfer (Helfand, Ruderman, and Shaham 1983; Joss and Rappaport 1983; Paczyński 1983; Savonije 1983). The small pulse period derivatives of millisecond pulsars indicate that the magnetic field has decayed to a small ($\sim 10^9$ G), but nonzero, strength (Kulkarni 1988). The evolutionary scenarios which account for the formation of millisecond radio pulsars suggest that LMXBs have millisecond period rotating neutron star primaries with magnetic fields of order 10^9 G. The discovery of quasi-periodic oscillations (QPOs) in LMXBs in 1985 supports this suggestion. QPOs have been observed in ~ 10 LMXBs (Lewin, van Paradijs, and van der Klis 1988; Hasinger and van der Klis 1989) including most of the brightest Galactic X-ray sources. In several popular models for explaining horizontal branch QPOs, including the beat frequency model (Alpar and Shaham 1985; Lamb *et al.* 1985), neutron star spin periods of ~ 10 ms and magnetic fields $\sim 10^9$–10^{10} G are predicted.

Sensitive searches for periodic pulsations at millisecond periods have yielded upper limits to the pulse fraction in the range 0.3%–3% (van der Klis *et al.* 1985; Middleditch and Priedhorsky 1986; Hasinger and van der Klis 1987; Norris and Wood 1987; Stella, White, and Priedhorsky 1987; Wood *et al.* 1987; van Paradijs *et al.* 1988). The lack of detected pulsations is not inconsistent with current models. The relatively weak magnetic fields are expected to yield small pulse fractions. These weak pulses are further diminished during propagation from the neutron star by atmospheric scattering effects (Brainerd and Lamb 1987; Wang and Schlickheiser 1987; Bussard *et al.* 1988) and gravitational lensing (Meszaros, Riffert, and Berthiaume 1988; Wood, Ftaclas, and Kearny 1988). Finally the most sensitive searches, utilizing long observations, must take into account Doppler smearing of the X-ray pulsations which are due to the binary motion of the neutron star (Middleditch and Priedhorsky 1986; Norris and Wood 1987; Wood *et al.* 1987).

In this paper we report on a search for coherent periodic pulsations from GX 9+1, the brightest Galactic X-ray source which has not been observed to emit QPOs. The data were obtained during a long (2.5 hr) continuous observation of GX 9+1 with the *EXOSAT Observatory*. We have been careful to correct the data for the (unknown) binary motion of the neutron star; this is done using a quadratic coherence recovery technique which efficiently searches the phase space of all likely orbits. The analysis was performed on a parallel computer, the Connection Machine CM-2. In § II we describe our search algorithm, including the coherence recovery technique and its parallel implementation. We describe the data and report the results of our search in § III. Finally we discuss the implications of our upper limits (§ IV).

II. THE SEARCH ALGORITHM

a) Coherence Recovery Technique

The sensitivity of any search for periodic variability from an astronomical source can be improved by increasing the signal-to-noise ratio in the data. For a source with a moderate photon count rate, such as a bright X-ray source observed with a moderate sized proportional counter array, this means long exposure times. In binary systems with short orbital periods, source motion can reduce sensitivity by causing a loss of coherence at the observer. Without restoration of phase coherence, weak signals become undetectable.

The orbital periods of LMXBs are typically 3–8 hr (Parmar and White 1988). Our 2.5 hr exposure of GX 9+1 is probably a large fraction of the source's (unknown) orbital period. It is necessary to use a coherence recovery technique to obtain the maximum sensitivity to coherent pulsations in the data. We use the quadratic coherence recovery technique of Wood *et al.* (1987, 1990). As this technique is explained in detail by Wood *et al.* (1990, hereafter W90), we give only a brief summary here for completeness.

For a pulsar in a circular orbit, the pulse arrival times are delayed or advanced with a sinusoidal modulation. Knowledge of the binary orbit enables the pulse arrival times to be corrected to a system barycenter. When the binary orbital parameters are unknown, a phase space of orbital parameters is searched. At each point in this phase space, the data is corrected for the test orbit, an FFT of the data is performed, and the power spectrum is searched for evidence of coherent pulsations. At the point of phase space which corresponds to the actual orbit, the pulsations will be present in a single channel of the power spectrum.

The full phase space for an unknown binary orbit has three dimensions (period, semi-major axis, and phase). A search through a three dimensional phase space is prohibitively expensive in terms of computer resources, especially for long data stretches. W90 shows that the optimal one-dimensional search strategy involves the application of quadratic time transformations. Each photon arrival time t is transformed quadratically to an effective arrival time t', where

$$t' = t + \alpha t^2 . \quad (1)$$

Here α is the quadratic transformation parameter. This method is mathematically equivalent to approximating the arc of the pulsar's orbit which is traced during the observation by a parabola. If the parabola which corresponds to a given parameter α is a good enough approximation, then the FFT of the quadratically transformed data will have most of the pulse power present in a single channel of the power spectrum.

The two parameters necessary to describe a search for pulsations using the quadratic coherence recovery technique are α_{max}, the largest quadratic parameter used, and $\delta\alpha$, the increment in the quadratic parameter between independent trials. The extrema for α occur when the pulsar is at conjunction with its binary companion relative to the observer. Fitting a parabola to a circular orbit and using Kepler's third law, W90 derives

$$\alpha_{max} = 1.79 \times 10^{-6} \mu (P_{orb}/1 \text{ hr})^{-4/3} (M_{tot}/M_{\odot})^{1/3} \text{ s}^{-1} , \quad (2)$$

where P_{orb} is the orbital period, M_1 is the mass of the pulsar primary, M_2 is the mass of the binary companion star, and $\mu \equiv M_2/(M_1 + M_2)$. In practice, orbital periods P_{orb} short relative to the data integration time T cannot be searched, since the pulsar moves over an appreciable fraction of its orbit during the observation and the parabolic approximation is no longer valid. For orbital periods $P_{orb} \gtrsim 4\pi T$, the power from a coherent signal near the Nyquist period will be recovered in a single channel (W90).

Similarly, the increment $\delta\alpha$ is chosen to correspond to the correction necessary for minimal pulse smearing, i.e., such that a periodic signal at the Nyquist period which is broadened by orbital motion uniformly over two channels in the power spectrum is recovered in a single bin. For a data stream consisting of N bins of duration τ, the integration time is $T = N\tau$ and the Nyquist period is $P_{Nyq} = 2\tau$. The increment in the quadratic parameter is (W90)

$$\delta\alpha = P_{Nyq}/2T^2 = 1/N^2\tau . \quad (3)$$

The number of transformations searched is

$$N_\alpha = 2\alpha_{max}/\delta\alpha , \quad (4)$$

since the quadratic parameter is allowed to vary from $-\alpha_{max}$ to $+\alpha_{max}$.

It is necessary to specify the confidence limit at which a detected signal is considered significant. The FFT power spectrum of an N-bin data set has $N/2$ independent spectral channels. For a signal at the Nyquist period, each transformation yields an independent search; for longer periods, the transformations are not independent. At $2P_{Nyq}$ every other transformation is independent, at $3P_{Nyq}$ every third transformation is independent, etc. If we define a degree of independence $\rho \equiv P_{Nyq}/P$, then the total number of independent transformations searched is

$$N_{tot} = N_\alpha \sum_{i=1}^{N/2} \rho_i , = N_\alpha (N/2 - 1)/2 , \simeq N_\alpha N/4 , \quad (5)$$

where the sum is over all independent channels in the power spectrum, ρ_i is the degree of independence in the ith spectral channel, and the period associated with the ith spectral channel is $(P_{Nyq}/i)(N/2)$. If we normalize the power spectra by the variance of the data to unity mean, then powers are exponentially distributed. The probability that the height of a single peak exceeds x in the presence of noise only, i.e., no signal, is $\exp(-x)$, and the probability of observing one or more peaks exceeding x after searching N_{tot} independent spectral channels is

$$P(>x) = 1 - (1 - e^{-x})N_{tot} , \simeq N_{tot} e^{-x} , \quad (6)$$

for large x.

Leahy *et al.* (1983) have shown that the pulse fraction A which produces a peak of height x in a normalized power spectrum, after coherence recovery, is

$$A = 2K_{\rm ftr}(P)\sqrt{[(x-1)/x_0]}\ , \qquad (7a)$$

where x_0 is the power in the zeroth spectral channel; for a normalized power spectrum, this is the DC power or the number of 1's in the data stream. $K_{\rm ftr}(P)$ is a period dependent correction factor for the finite time resolution of the data for signals near the Nyquist period and the loss of sensitivity when the pulse period is not exactly one of the $N/2$ independent periods examined in the FFT (Leahy *et al.* 1983),

$$K_{\rm ftr}(P) = 1.137(\pi\tau/P)/\sin(\pi\tau/P)\ . \qquad (7b)$$

The correction factor $K_{\rm ftr}(P)$ ranges from 1.137 for long periods to 1.787 at the Nyquist period.

We have not corrected the pulse fraction upper limits for sensitivity lost because of the rebinning of the data for the time transformation (eq. [1]) or the mismatch of the quadratic approximation to the actual binary orbit (eq. [2]). Simulations show that the appropriate correction factor is small (Wood *et al.* 1987), and it is addressed analytically in W90.

b) Implementation on the Connection Machine

As we describe in § III, the GX 9+1 data set consists of 36 M contiguous data points. (We use 1 k = 1048 = 2^{10} and 1 M = 1 k × 1 k = 1,048,576 = 2^{20}.) We can divide the data into k independent data sets for processing, where each data set contains $N = 36$ M/k data points. In order to obtain the maximum sensitivity possible, we want to maximize N and thus minimize k. The limit on N is set by the largest FFT which can be performed. At NRL, the Space Science Division VAX 11/785 is configured so that the largest real FFT which can be performed is $N = 512$ k (2^{19}) points long and takes ~15 minutes. On the Central Computation Facility Cray XMP-24, a 1 M (2^{20}) point real FFT can be performed in ~1.3 s. The Connection Machine Facility CM-2 can be programmed to perform a 4 M (2^{22}) point complex FFT in 12.6 s. We thus chose to search the GX 9 + 1 data for pulsations using a Connection Machine CM-2, a data parallel, or SIMD (single instruction, multiple data) computer (Hillis 1985, 1987). In a data parallel computer, each processor has memory associated with it so the data must be distributed among the individual processors; however, each active processor executes the same instruction at each step of execution.

We have written an efficient complex FFT for the CM-2 in Paris, the Connection Machine assembly language (Hertz 1990; Norris *et al.* 1989). The CPU run time for this FFT scales as log (N) for $N \le 16$ k, and N log (N) for 16 k $< N \le 4$ M. A 1 M point complex FFT takes 3.0 s on the CM-2, and a 4 M point complex FFT takes 12.7 s.

The search algorithm is implemented on the CM-2 as follows. A 4 M point data set is read into the VAX 8800 front end. The 16 k physical processors on the CM-2 are configured into 4 M virtual processors, and one datum is stored in each virtual processor. As described in § III, the data consists of 1's and 0's only, so only 1 bit of memory is used in each virtual processor for storage. A value of α is chosen, and the data is transformed using the quadratic time transformation (eq. 1). Each virtual processor corresponds to a time bin; after the transformed time t' is calculated simultaneously in every virtual processor, that processor sends its datum to the processor which corresponds to t' using the intra-processor router. The FFT of the transformed data is calculated in place using the Hertz (1990) parallel FFT. The power spectrum is normalized by dividing it by the mean power in the spectrum (excluding the DC component). For data dominated by Poisson statistics, the mean power is equivalent to the variance in the data, which is the number of counts in the data. Finally, each spectral channel is examined in parallel, and the highest peak is recorded. The entire process takes 15.3 s of CPU time, most of which is spent calculating the FFT.

Since the original data is preserved in CM memory, a new value of α can be searched without reading the data from disk again. In a typical run, we allocate the CM-2 for an hour and search through 250 transformations. We keep track of the highest peaks detected in the power spectra, and the quadratic parameters that they correspond to, for each data set. If a significant peak is detected, we can examine that transformation in more detail at a later time.

c) Considerations of Computational Cost

The computational cost of a complete search for periodic signals using the quadratic coherence recovery technique can be estimated straightforwardly. If the complete data set has M points, and it is divided into k segments of $N = M/k$ points each, then the number of FFTs which need to be computed scales as

$$N_{\rm FFT} \propto kN_\alpha\ , \\ \propto kN^{2/3}\ , \qquad (8)$$

where we have used eqs. (2)–(4) and assumed that the minimum orbital period searched is $P_{\rm orb} = 4\pi T \propto N$. The CPU time required to perform a FFT scales as N log (N); for large N, N log (N) $\propto N$. Thus the total CPU time required to perform a complete search scales as

$$\mathrm{CPU_{tot}} \propto kN^{5/3}\ . \qquad (9)$$

In Table 1 we show the approximate computational time

TABLE 1

COMPUTATIONAL COSTS FOR PULSAR SEARCH USING QUADRATIC COHERENCE RECOVERY TECHNIQUE

				VAX		CRAY		CM-2	
k	N	$2N_\alpha$	$N_{\rm FFT}$	per FFT	all FFT	per FFT	all FFT	per FFT	all FFT
9.........	4 M	2913	26217	...	...	...	...	12.7 s	92.5 hr
18.........	2 M	1835	33030	...	...	...	...	6.1	56.0
36.........	1 M	1157	41652	...	...	1.3 s	15.0 hr	3.0	34.7
72.........	512 k	729	52488	15 minutes	1.5 yr	0.6	8.8	1.4	20.4
144.........	256 k	459	66096	7.1	0.9	0.3	5.5	0.7	12.9

NOTE.—The computational cost for the pulsar search in CPU time is ~20% more than the FFTs alone.

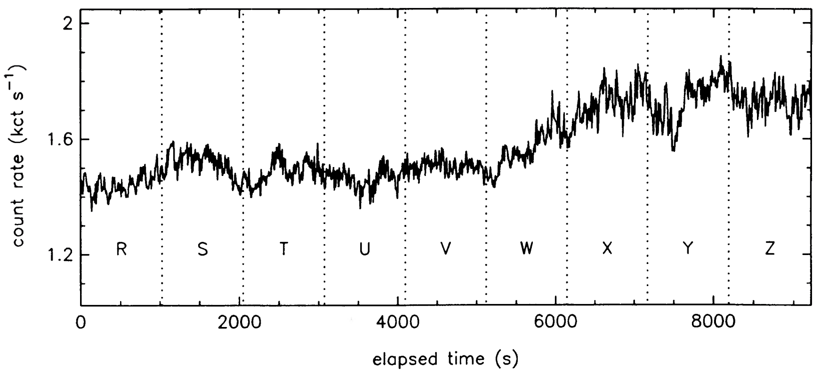

FIG. 1.—The light curve of GX 9+1 obtained with the *EXOSAT* ME on 1985 December 21. The 0.25 ms data has been binned into 8 s bins and corrected for undetected multiple counts arriving during a single 0.25 ms interval. The nine 17 minute data segments, "*R*" through "*Z*," which are searched independently for millisecond pulsations, are indicated.

necessary to search for pulsations in the data described in § III. This data has $\tau = 0.25$ ms and $M = 36$ M. We assume that the companion star has a mass $M_2 < 0.9\ M_\odot$ and that the neutron star primary has $M_1 = 1.4\ M_\odot$ when estimating $\delta\alpha$ (eq. 2), and we step α by $\delta\alpha/2$ so that phase space is oversampled. With these parameters

$$N_\alpha = 0.11 N^{2/3} . \qquad (10)$$

The search reported here, which used $N = 4$ M and $k = 9$, required 26,217 FFTs and took ~5 CPU days on the CM-2.

III. OBSERVATIONS AND RESULTS

a) X-Ray Observations

GX 9+1 was observed by the Medium Energy Experiment (ME) on board the *EXOSAT Observatory* (White and Peacock 1988) on 1985 September 21. The source was observed using the HTR4 fast timing mode with 0.25 ms time resolution. This is the highest time resolution available with the *EXOSAT* ME. The long *EXOSAT* orbit made it possible to obtain over 2.5 hr of continuous data at this time resolution. The lack of windows or dropouts in the data simplified the analysis.

Each of the 36 M data bins consists of a single bit. This bit indicates whether any photons were observed during the 0.25 ms corresponding to an individual time bin. Photons were observed during 32% of the time bins. If the source had a constant flux, Poisson statistics imply that ~5.7% of the time bins, or ~22% of the time bins during which at least one photon was detected, represent times when more than one photon arrived. In Figure 1 we show the light curve of GX 9+1 for the 2.5 hr observation. We have binned the data into 8 s bins in Figure 1, and the count rate is corrected using Poisson statistics for the counts lost when more than one photon arrived during a single 0.25 ms interval.

As 4 M point FFTs are the largest which we have the capability of performing (§ II*c*), we divided the data into nine segments. Each segment contains 4 M data points and spans ~17 minutes (1024 s) of observing time. The segments, labeled "*R*" through "*Z*," and the start times on 1985 September 21 are listed in Table 2 and indicated in Figure 1.

b) Results of the Pulsar Search

Our search can be complete only for orbits longer than 4π times the observation length, i.e., longer than ~3.6 hr. The only LMXBs with shorter periods known are the ultrashort period LMXBs, with $P_{orb} < 1$ hr, and 4U1323−62, with $P_{orb} = 2.9$ hr (Parmar and White 1988). We have chosen α_{max} such that our search is complete for a 1.4 $M_\odot$ pulsar with a binary companion whose mass is $< 0.9\ M_\odot$. Putting these constraints into eq. (2), we obtain $\alpha_{max} = 1.7 \times 10^{-7}$ s^{-1}. Good coverage is still provided for shorter orbital periods or heavier companion masses; however all of the pulsed energy will not be recovered in a single spectral channel. If GX 9+1 has $P_{orb} < 3.6$ hr, then the upper limits to pulse fraction are slightly higher than that reported here.

For our data sets ($N = 4$ M, $\tau = 1/4096$ s $\simeq 0.25$ ms), the critical increment in α is 2.3×10^{-10} s^{-1}. We have used an increment one-half this value, $\delta\alpha = 1.15 \times 10^{-10}$ s^{-1}, so that phase space is oversampled by a factor of 2. This diminishes the chance that a signal will be missed because it fell between two spectral channels. The 2 M spectral frequencies searched

TABLE 2

SEARCH FOR MILLISECOND X-RAY PULSATIONS FROM GX 9+1

Segment	Start time (UT)	Hits	Peak	Confidence level	Amplitude	3 σ UL
R	00:13:18.323	1245701	24.7	0.029	0.0087	0.0092
S	00:30:22.323	1297169	28.2	0.0009	0.0092	0.0090
T	00:47:26.323	1276488	24.4	0.039	0.0086	0.0090
U	01:04:30.323	1259998	22.5	0.23	0.0083	0.0091
V	01:21:34.323	1288814	22.5	0.23	0.0082	0.0090
W	01:38:38.323	1331028	23.0	0.14	0.0081	0.0089
X	01:55:42.323	1436830	23.8	0.071	0.0080	0.0085
Y	02:12:46.323	1446173	25.4	0.014	0.0082	0.0085
Z	02:29:50.323	1445869	27.8	0.0013	0.0086	0.0085
Average		1336452	28.2	0.0009	0.0090	0.0088
Total observation		12028070	28.2	0.008	...	...

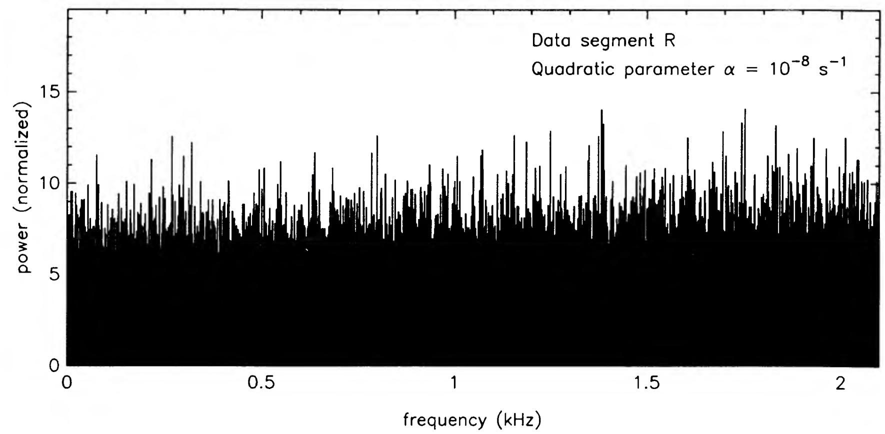

FIG. 2a

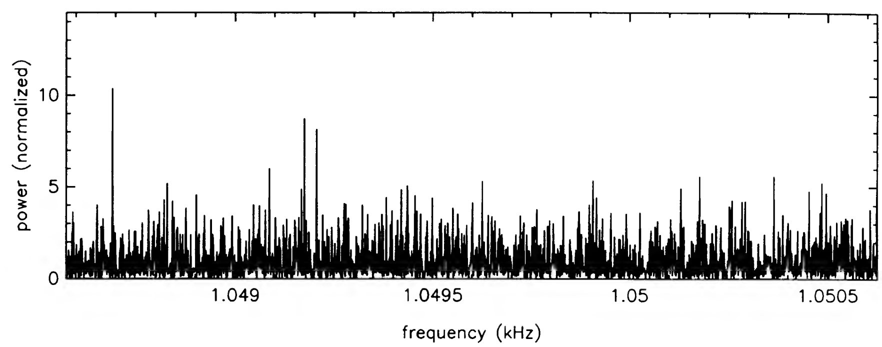

FIG. 2b

FIG. 2.—The power spectrum of data segment "*R*" from the *EXOSAT* ME observation of GX 9+1 after the data has been quadratically transformed with quadratic parameter $\alpha = 10^{-8}$ s^{-1}. (*a*) The 2 M independent powers are plotted. The frequency range, ~1 mHz to ~2 kHz, corresponds to periods between 0.5 ms and 17 minutes. (*b*) The section of the power spectrum near 1 kHz is plotted at full resolution; 2 k of the 2 M powers are shown with a resolution of 1 mHz.

span the range of periods from the Nyquist period ($P_{\rm Nyq} = 0.5$ ms) to the observation length ($T = 17$ minutes). With this choice of parameters, we searched 2957 possible binary orbits for each of the 9 data sets. In Figure 2 we show the power spectrum corresponding to correcting data segment "*R*" for one possible binary orbit ($\alpha = 10^{-8}$ s^{-1}). A 3 σ detection, which corresponds to a 99.73% confidence limit, requires a peak in the power spectrum to exceed 27.1.

In Table 2 we show the results of the millisecond pulsar search. For each data segment "*R*" through "*Z*," we show the number of 0.25 ms bins during which at least one photon was detected (hits), the peak power in the 2957 power spectra searched for that data segment (peak), the confidence limit (eq. 6) if only one data segment had been seached (conf), the pulse fraction (eq. 8) (amp), and the 3 σ upper limit to the pulse fraction (3 σ UL). The pulse fractions (amp, 3 σ UL) have not been corrected for finite time resolution effects (see eq. 7). At the bottom of Table 2 we show the same information for an average data segment.

We also show the confidence limit for the entire search when all nine data segments are taken into account, where a 3 σ detection corresponds to a peak in the power spectrum of 29.3. The probability that the highest observed peak is due to random fluctuations is ~0.008; this corresponds to a 2.7 σ detection, which is below our *a priori* threshold of 3 σ. Applying the correction for finite time resolution, we conclude that any pulsations in GX 9+1, have observable pulse fractions less than 1.6% for periods between 0.5 ms and 1 ms, less than 1.2% for periods between 1 ms and 3 ms, and less than 1.0% for periods between 3 ms and 17 minutes (Table 3).

IV. DISCUSSION

We have searched for coherent pulsations in an *EXOSAT* observation of the Galactic X-ray sources GX 9+1. None were detected and we set a 3 σ upper limit to the pulsed fraction of 1.1%–1.7% for all likely binary orbits. Although we do not detect millisecond pulsations from GX 9+1, this search is significant because: (1) we have searched a broad range of possible periods (0.5 ms to 17 minutes); (2) we have increased sensitivity through the use of an unusually long continuous X-ray observation (36 M 0.25 ms samples in 2.5 hr); (3) we have corrected for the unknown binary motion of the source through the use of an efficient coherence recovery technique; and (4) we have developed and implemented a parallel FFT and pulse search routine on a data parallel computer.

The upper limits that we attained are not significantly lower

TABLE 3

LIMITS ON PULSE FRACTIONS FOR GX 9+1

Pulse period (P)	3 σ Upper limit to pulsed fraction
0.5 ms	0.0164
1.0	0.0116
2.0	0.0107
>3.0	0.0105

than those previously reported in searches for millisecond pulses in QPO sources (see Lewin, van Paradijs, and van der Klis 1988), in part because we have examined many more power spectra in searching phase space for the appropriate binary motion. In fact, we searched N_α, or 1479, times as many power spectra. If we had ignored the possibility of binary motion, and searched our nine data segments with $\alpha = 0$ only, then our threshold pulsed fraction would have been 1.0% rather than 1.2% for a 1 ms pulse period.

GX 9+1 is among the brightest LMXBs from which QPOs have not been observed. Hasinger and van der Klis (1989) classify GX 9+1 as an atoll source on the basis of its color-color diagram and power spectrum. According to their classification, atoll sources never show QPOs. They also postulate that atoll sources may have shorter periods than QPO sources (which Hasinger and van der Klis 1989 refer to as *Z*-sources). If this is true, then the need to use a coherence recovery technique when searching for coherent pulsations is even stronger.

There is no contradiction between our upper limits to coherenet pulsations from GX 9+1 and theories of LMXBs and millisecond spin periods. We know from the absence of strong pulses and the presence of X-ray bursts that LMXBs have small magnetic fields ($<10^9$ G). The emitted pulse fraction is expected to be small ($<1\%$) due to the weak magnetic field. There are many mechanisms for further reducing the observed pulse fraction, including magnetospheric effects and gravitational lensing. In order to detect millisecond pulsations in LMXBs, it will be necessary to have better signal-to-noise, as well as detailed knowledge of the binary orbit. Better signal-to-noise ratios can be obtained with very large area detectors such as the 100 m^2 X-ray Large Array (Wood and Michelson 1988). The detection of orbital variability in the bright Galactic bulge X-ray sources, such as GX 9+1, will probably require high throughput timing observations from instruments such as the X-Ray Large Array, the X-Ray Timing Explorer, or the European X-Ray Multiple Mirror.

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