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DISCOVERY OF THE QUASI-PERIODIC OSCILLATIONS FROM V0332+53

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ABSTRACT

The discovery of quasi-periodic oscillations (QPOs) in the X-ray flux from the recurrent transient X-ray pulsar V0332+53 is reported. The centroid frequency, full width at half-maximum (FWHM), and the relative root mean square (rms) amplitude of the QPOs are $(5.1 \pm 0.5) \times 10^{-2}$ Hz, $(3.3 \pm 1.5) \times 10^{-2}$ Hz, and 4.8% ± 1.2%, respectively. The beat frequency model is tested using these results and previously reported QPOs from other X-ray binary pulsars.

Subject headings: pulsars: individual (V0332+53) — stars: oscillations — X-rays: stars

1. INTRODUCTION

The recurrent transient X-ray pulsar V0332+53 was discovered in 1973 with *Vela 5B* during a bright outburst (~1 crab) (Terrell & Priedhorsky 1983, 1984). A second flare of this pulsar was detected with *Tenma* in 1983 (Tanaka et al. 1983). Follow-up observations with *Tenma* and *EXOSAT* revealed a 4.37 s pulsation period and a 34.25 day orbital period with an orbital eccentricity of 0.31 (Stella & White 1983; Stella et al. 1985). An optical counterpart was identified as a reddened B star (Argyle 1983; Kodaira 1983; Honeycutt & Schlegel 1983). The distance to the source was estimated from the optical reddening to be 2.2–5.8 kpc (Corbet, Charles, & van der Klis 1986). A cyclotron absorption feature at 28.5 keV was discovered in the X-ray spectrum of V0332+53 with *Ginga* (Makishima et al. 1990a), which implies a neutron star surface magnetic field of 2.5×10^{12} G.

Quasi-periodic oscillations (QPOs) from X-ray binary pulsars have thus far been reported from five sources: EXO 2030+375 (Angelini, Stella, & Parmar 1989), 4U 0115+63 (Soong & Swank 1989), SMC X-1 (Angelini 1989; Takeshima 1992), X1627−673 (Shinoda et al. 1990), and Cen X-3 (Takeshima et al. 1991). The origin of the QPOs is not clear, however, many models have so far been proposed (Lewin, van Paradijs, & van der Klis 1988 and references therein). Among them, the beat frequency model (BFM; Alpar & Shaham 1985; Lamb et al. 1985; Alpar 1986; Elsner, Shibazaki, & Weisskopf 1987; Shibazaki & Lamb 1987), which was proposed to explain the horizontal branch QPOs from low-mass X-ray binaries, is generally regarded as the most plausible model for QPOs from X-ray pulsars. There are also some other models of QPOs, however, some difficulties in applying these models to the QPOs from X-ray pulsars were pointed out in previous work (Angelini et al. 1989; Shinoda et al. 1990; Takeshima et al. 1991). In the BMF, QPOs originate from the inhomogeneity of the accreting matter at the inner edge of the accretion disk. The inner edge corresponds to the Alfvén radius where the magnetic energy density of the neutron star is comparable to the kinetic energy density of the accreting matter. The QPO frequency is the difference between the frequency of the neutron star rotation and that of the accreting disk matter at the Alfvén radius assumed to be in Keplerian motion, that is, $\nu_{\rm QPO} = \nu_{\rm K} - \nu_{\rm spin}$.

In this paper we describe the observed properties of QPOs from V0332+53 obtained with *Ginga*, given observations on physical process of QPO production and discuss the systematic difficulties in BFM to explain QPOs from X-ray binary pulsars.

2. OBSERVATIONS AND RESULTS

A sudden flare up of V0332+53 on 1989 September 19 was found with the All Sky Monitor (ASM; Tsunemi et al. 1989) on board *Ginga* and reported by Makino et al. (1987). We obtained observations using the Large Area Proportional Counter (LAC; Turner et al. 1989) on board *Ginga* twice during the outburst; from September 19, 21:41 (UT) to September 20, 21:19 and from October 1, 12:31 to 22:21. The results of the spectral analysis of the data have already been published by Makishima et al. (1990a) which revealed the presence of a cyclotron feature. The detailed log of observations with time resolution higher than 0.5 s/bin is summarized in Table 1 accompanied by the averaged X-ray luminosity in the energy range of 2.3–37.2 keV, assuming a source distance of 3 kpc. A data-folding method was employed to determine the apparent pulse periods with heliocentric correction for separate four intervals which are also given in Table 1. Since the determined apparent pulse period of data A–D (see Table 1) is longer than the maximum apparent period in the orbital phase reported by Makishima et al. (1990b), the long-term spin-down tendency is strongly suggested. In contrast to the previous observations (Stella et al. 1985; Makishima et al. 1990b), the pulse fraction (2.3–37.2 keV) is relatively large, up to 10% peak-to-peak amplitude during the observations.

For the power spectral analysis, we used the data with the highest time resolution, 7.8 ms/bin (Data A, C, J, and L indicated in Table 1) to minimize the beat effects between the pulsation of V0332+53 and the data bin width. We calculated Fourier power spectral densities for every continuous 128 s data interval (16,384 bins) and obtained 15 and 60 element ensembles for the data obtained on September 19 and October 1, respectively. In calculating power spectra, we did not sub-

TABLE 1

OBSERVATION LOG OF V0332+52

Data Label	Date (1989)	UT (hh:mm) Start–Stop	Exposure (s)	Time Resolution (s/bin)	L_X[a] (ergs s^{-1})	Apparent Period[b] (s)
A	Sep 19	21:41–22:00	1119.5	0.00781	2.1×10^{37}	...
B		22:48–22:50	128.0	0.0625	2.0×10^{37}	...
C		22:50–23:06	956.0	0.00781	2.1×10^{37}	A–D
D		23:06–23:08	96.0	0.0625	2.2×10^{37}	4.37637 ± (9)
E	Sep 20	19:54–20:18	1459.5	0.0625	2.1×10^{37}	...
F		21:02–21:05	192.0	0.50	2.1×10^{37}	...
G		21:05–21:17	687.9	0.0625	2.1×10^{37}	E–H
H		21:17–21:19	122.5	0.50	2.0×10^{37}	4.37634 ± (8)
I	Oct 1	12:31–12:39	512.0	0.0625	3.1×10^{37}	I–J
J		13:40–17:36	7620.9	0.00781	3.1×10^{37}	4.37549 ± (2)
K		18:24–18:26	128.0	0.0625	3.2×10^{37}	K–L
L		18:26–18:46	1091.5	0.00781	3.0×10^{37}	4.3753 ± (5)

[a] X-ray luminosity is for the energy range of 2.3–37.2 keV and the distance of 3 kpc is assumed.

[b] Indicated uncertainties are the period difference which decreases the χ^2 value by 1.0 from the maximum value in folding technique with DOF of 50.

tract the background count because the background count rate is less than 3% of the source count rate. Besides, the power spectrum of the blank sky data in the useful frequency range is a white noise, and it has much less power densities than those of time variability of V0332+53. Next, we made ensemble-averaged power spectra and then normalized the Fourier power densities by dividing by the square of the averaged source intensity without background count. Figures 1*a* and 1*b* show the intensity normalized power spectra calculated from the data of September 19 and October 1, respectively.

One can see a clear sharp spike at 0.2286 Hz corresponding to the fundamental harmonic of the 4.37 s coherent pulsation. In addition, a broad hump around 0.05 Hz can be seen in Figure 1*b*. A similar feature is not apparent in Figure 1*a*. As we are most interested in the QPO feature, we concentrate on the power spectrum shown in Figure 1*b* hereafter.

In order to check the statistical significance of the broad hump feature, a χ^2-fit and an F-test (i.e., Bevington & Robinson 1992 were applied to the power spectrum. First, we employed three model components to fit the observed power spectrum: (1) narrow line for coherent pulsation, (2) broken power-law function with indices of 0 (fixed) and $-\alpha$ in the lower and higher frequencies, respectively, for the continuum, and (3) a Lorentzian for low-frequency noise whose center frequency is fixed to 0. The resulting χ^2-value is 221 for 138 degrees of freedom. Consequently, we added another Lorentzian model component to take account of the broad hump around 0.05 Hz. This addition to the model reduced the χ^2-value to 179 for 135 degrees of freedom. From an F-test, we can conclude the hump around 0.05 Hz is significant with more than 99.9% confidence level while the χ^2-value is still not acceptable. The best-fit parameters of these QPO components are summarized in Table 2.

To investigate the energy dependence of the QPOs, we calculated the ensemble average of the intensity-normalized power spectra for the three energy bands of 2.3–7.0, 7.0–14.0,

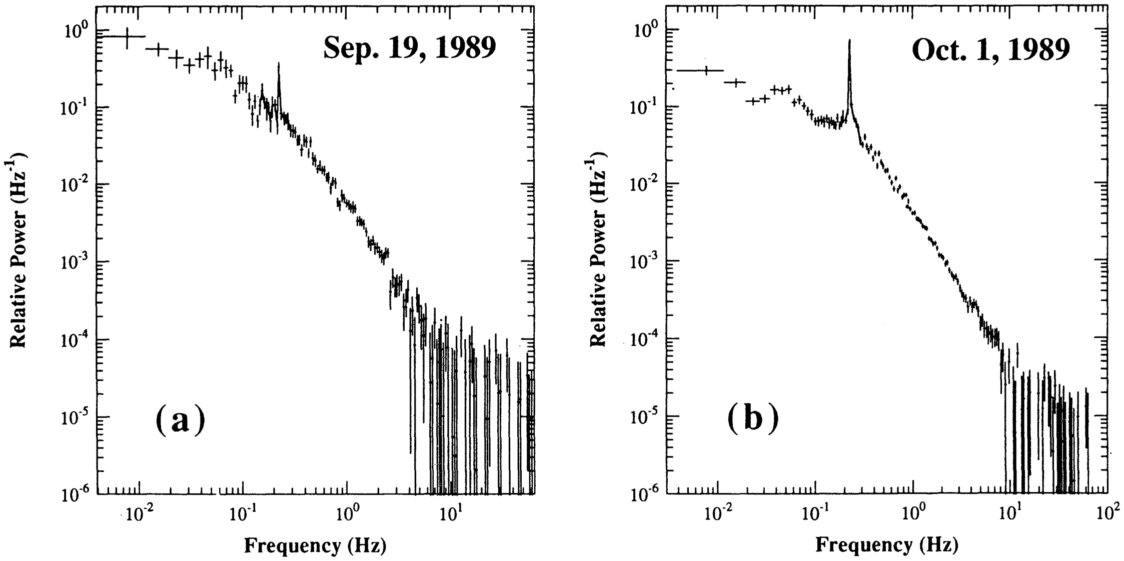

FIG. 1.—Intensity normalized power spectral densities of V0332+53 obtained between 1989 September 19–20 (*a*) and October 1 (*b*)

TABLE 2

BEST-FIT PARAMETERS OF THE QPOs

Energy (keV)	Centroid Frequency (Hz)	FWHM (Hz)	RMS Amplitude	χ^2 (DOF = 135)
2.3–37.2............	$(5.1 \pm 0.5) \times 10^{-2}$	$(3.3 \pm 1.5) \times 10^{-2}$	4.8% ± 1.2%	179
2.3–7.0.............	$(5.0 \pm 0.7) \times 10^{-2}$	$(4.4 \pm 2.1) \times 10^{-2}$	5.6 ± 1.2	164
7.0–14.0............	$(4.8 \pm 0.6) \times 10^{-2}$	$(3.7 \pm 1.7) \times 10^{-2}$	5.5 ± 1.1	193
14.0–37.2............	$(4.9 \pm 0.6) \times 10^{-2}$	$(3.3 \pm 1.5) \times 10^{-2}$	4.5 ± 1.0	110

NOTE.—Indicated uncertainties are 90% confidence levels.

and 14.0–37.2 keV from the data obtained on October 1. A χ^2 fit was also applied to these energy-divided power spectra. The best-fit parameters for the QPOs are also summarized in Table 2. We could not find any significant energy dependence of the QPO parameters.

In the count rate time history, we can see directly the flux modulation with timescale of ~20 s that corresponds to the QPO frequency (see Fig. 2). This kind of flux modulation is intermittently seen in the count rate time history. Although the number of coherent cycles is only 3–4, this is still too many to explain the broad QPO peak. Most of each power spectrum that is not ensemble averaged has a sharper peak around the QPO frequency. Thus, it is suspected that the broadening of the QPO peak is due to the frequency drift of the modulation, as also suggested for the QPOs from a rapid burster (Dotani et al. 1990).

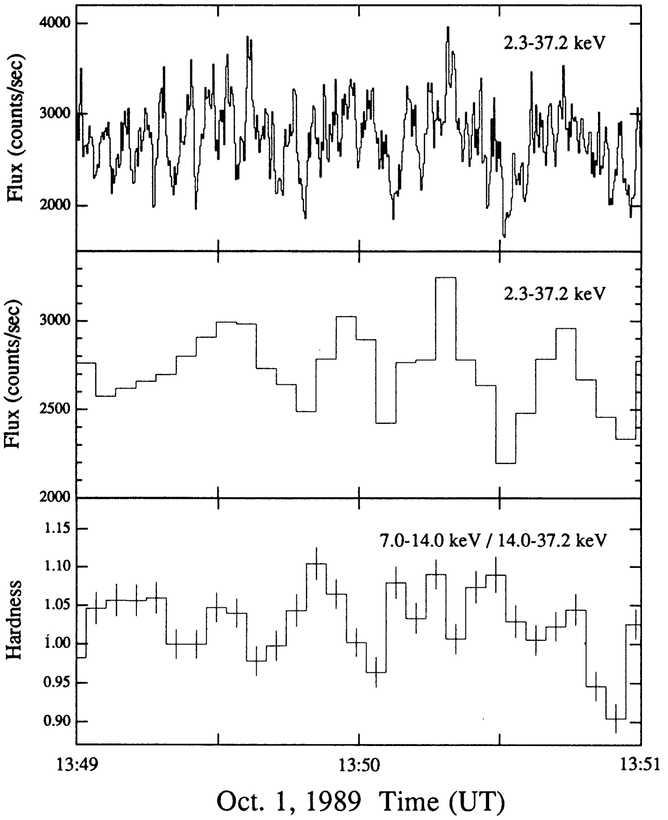

FIG. 2.—An examples of the count rate time history observed on October 1. *Top panel*: bin width of 0.25 s bin; *middle panel*: bin width of 4.25 s/bin. The flux modulation with time scale of ~20 s seems responsible for QPO. *Bottom panel*: spectral hardness (7.0–14.0 keV/14.0–37.2 keV). There is no clear correlation between the counting rate and the hardness.

3. DISCUSSION

We discovered QPOs from the 4.37 s X-ray pulsar V0332+35 with *Ginga*. Since the strength of the surface magnetic field is available for V0332+53 (Makishima et al. 1990a), this provides a strict test of the BFM for QPOs from X-ray pulsars. It is not clear whether an accretion disk is formed or is not formed in the V0332+53 system. In the BFM, however, QPO frequency is the difference between the Kepler frequency at the inner edge of accretion disk (Alfvén radius) and the spin frequency of the magnetized neutron star. Thus the existence of the accretion disk is intrinsically assumed in the BFM. From the accretion disk theory for binary X-ray pulsars developed by Ghosh & Lamb (1979a, b, hereafter G&L) the Alfvén radius r_A is expressed as

$$r_A = 2.4 \times 10^8 \left(\frac{\alpha}{0.52}\right)\left(\frac{M_{NS}}{1.4\, M_\odot}\right)^{1/7}\left(\frac{\mu/R_{NS}^3}{2.5 \times 10^{12}\ \mathrm{G}}\right)^{4/7} \times \left(\frac{R_{NS}}{10^6\ \mathrm{cm}}\right)^{10/7}\left(\frac{L_X}{3.1 \times 10^{37}\ \mathrm{ergs\ s^{-1}}}\right)^{-2/7} \ (\mathrm{cm})\,,$$

where α, M_{NS}, $M_\odot$, μ, R_{NS}, and L_X are the ratio of the Alfvén radius of disk accretion to that of spherical accretion (G&L), the mass of the neutron star, the mass of the Sun, the magnetic dipole moment of the neutron star, the radius of the neutron star, and the source luminosity, respectively. Here μ/R_{NS}^3 corresponds to the strength of the surface magnetic field of the neutron star.

Alternatively, we can calculte the Alfvénic radius (r'_A) by assuming the BFM. Since the QPO frequency (ν_{QPO}) is the difference between the Kepler frequency (ν_K) and the spin frequency (ν_{spin}) of the neutron star, that is, $\nu_K = \nu_{QPO} + \nu_{spin}$, the Alfvén radius can be written as

$$r'_A = \left(\frac{GM_{NS}}{4\pi^2\nu_K^2}\right)^{1/3} = 3.93 \times 10^8 \left(\frac{\nu_{QPO} + \nu_{spin}}{0.051 + 0.229}\right)^{-2/3}\left(\frac{M_{NS}}{1.4\, M_\odot}\right)^{1/3} \ (\mathrm{cm})\,.$$

The value of r'_A estimated from the BFM is about 2 times larger than that calculated from the G&L. Uncertainties exist in the value of α and L_X. The difference of a factor of 2 is, however, too large for α since multiplying 2 to nominal α-value, α becomes larger than unity. This means the radius at the inner edge of the accretion disk is not smaller than the Alvén radius with spherical accretion. L_X has two origins of uncertainty: the source distance and the X-ray beaming factor. But because Alfvén radius is proportional to $L_X^{-2/7}$, the difference of factor 2 requires about 10 times larger luminosity. Such a large underestimate does not seem realistic. Therefore, the inconsistency between r_A and r'_A suggests that the BFM does not work as a mechanism to produce QPOs at least from V0332+53.

TABLE 3

QPOs from X-Ray Pulsars as a Test of BFM

Pulsar Name	$\nu_{\rm spin}$ (Hz)	$\nu_{\rm QPO}$ (Hz)	BFM r'_A (10^8 cm)	G&L r_A (10^8 cm)	BFM Fastness	References
SMC X-1	1.410	0.010	1.33	1.08	0.99	Angelini 1989
X0115+63	0.277	0.062	3.46	1.40	0.82	Soong & Swank 1989
V0332+53	0.229	0.051	3.93	2.37	0.82	This work
Cen X-3	0.207	0.035	4.33	1.48	0.86	Takeshima et al. 1991
X1627−673	0.132	0.040	5.47	3.48	0.76	Shinoda et al. 1990
EXO 2030+375	0.024	0.213	4.39	1.48	0.10	Angelini et al. 1989

V0332+53 is the sixth X-ray pulsar to exhibit QPOs so far. These QPO sources belong to the group of X-ray pulsars with relatively short pulse periods. It may be possible that there exists a selection effect that many spikes of the higher harmonics prevent finding QPO structure in power spectra for pulsar with relatively long pulse period. We calculated the Alfvén radii for these pulsars with the BFM and with G&L (Table 3). In this calculation a surface magnetic field of strength 2×10^{12} G is assumed for the pulsars SMC X-1, Cen X-3, X1627−673, and EXO 2030+375. Since values of the surface magnetic field determined from the cyclotron resonant scattering feature in the energy spectra from X-ray pulsars concentrate in the range of (1–4) $\times 10^{12}$ G (Makishima et al. 1990a), the above assumption may be reasonable. The surface magnetic field of 1.0×10^{12} G is known for X0115+63 (Wheaton et al. 1979; White, Swank, & Holt 1983; Nagase et al. 1991). One can immediately see from Table 3 that Alfvén radii estimated from the BFM are systematically 1.2–3 times larger than those estimated from G&L. Such a systematic overestimate of Alfvén radii with the BFM may originate from the fact that almost all the frequencies of QPOs in X-ray pulsars are much smaller than that of the coherent pulsations. In other words, the fastness parameter (G&L), which is a ratio of the spin frequency to the Kepler frequency at the Alfvén radius, is near unity for these sources assuming the BFM (see Table 3). Thus, if the BFM works these QPO sources must be nearly corotators, while the majority of these pulsars clearly exhibit spin-up tendency (Nagase 1989 and references therein). From this evidence, it is difficult to believe that the BFM is the mechanism that produces QPOs in X-ray binary pulsars. Thus, we have no applicable model for QPOs from X-ray binary pulsars now.

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