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DISCOVERY OF A VARIABLE-FREQUENCY 50–60 Hz QUASI-PERIODIC OSCILLATION ON THE NORMAL BRANCH OF GX 17+2

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ABSTRACT

We report the discovery, with the *Rossi X-Ray Timing Explorer*, of a 50–60 Hz quasi-periodic oscillation (QPO) in GX 17+2. The QPO is seen when GX 17+2 is on the normal branch in the X-ray color-color diagram. Its frequency initially increases from 59 to 62 Hz as the source moves down the normal branch, but below the middle of the normal branch it decreases to ~50 Hz. Together with this frequency decrease, the QPO peak becomes much broader, from ~4 Hz in the upper part of the normal branch to ~15 Hz in the lower normal branch. The rms amplitude remains approximately constant between 1% and 2% along the entire normal branch. From a comparison of the properties of this QPO with those of QPOs previously observed along the normal branch in other Z sources, we conclude that it is most likely the horizontal-branch QPO (HBO). However, this QPO displays a number of unusual characteristics. The decrease in the QPO frequency along the lower normal branch is not in agreement with the predictions of the beat-frequency model for the HBO unless the mass flux through the inner disk decreases as the source moves down the lower normal branch. We tentatively suggest that the required decrease in the mass flux through the inner disk is caused by an unusually rapid increase in the mass flux in the radial inflow as GX 17+2 moves down the normal branch. Assuming that this explanation is correct, we can derive an upper bound on the dipole component of the star's magnetic field at the magnetic equator of 5×10^9 G for a 1.4 $M_\odot$ neutron star with a radius of 10^6 cm.

Subject headings: accretion, accretion disks — stars: individual (GX 17+2) — stars: neutron — X-rays: stars

1. INTRODUCTION

GX 17+2 is a bright, low-mass X-ray binary. Hasinger & van der Klis (1989) classified it as a Z source by using its correlated spectral and fast timing behavior. Z sources trace out a Z shape in the color-color diagram. The three limbs of the Z are called the horizontal branch (HB), the normal branch (NB), and the flaring branch (FB). Variations in the total mass accretion rate are thought to produce the Z track. The properties of the rapid X-ray variability in Z sources are closely related to the positions of the sources on their Z tracks (see van der Klis 1995 for a review). On the horizontal branch, a quasi-periodic oscillation (QPO) can be seen, which varies in frequency from as low as 12 Hz at the left end of the HB to as high as 55 Hz near the HB-NB junction. The frequency of this HB QPO (or HBO) at the junction depends on the source (Cyg X-2: ~55 Hz, Wijnands et al. 1996; GX 5−1 and GX 340+0: ~50 Hz, Lewin et al. 1992; Penninx et al. 1991; Kuulkers et al. 1994; Kuulkers & van der Klis 1996; and probably ~45 Hz for Sco X-1, van der Klis et al. 1996). The HBO is sometimes still detectable in the upper part of the NB. In all observations of Z sources up to now, on the NB the frequency of the HBO remained approximately constant at the value it had at the junction. The HBO frequency is thought to be the beat frequency between the Keplerian frequency at the inner edge of the accretion disk and the spin frequency of the neutron star (Alpar & Shaham 1985; Lamb et al. 1985). When the mass accretion rate increases, the disk penetrates deeper into the magnetic field of the neutron star, and the Keplerian frequency of the inner edge of the disk, and hence the frequency of the HBO, increases. Near the middle of the NB, the HBO is sometimes seen together with another QPO with a frequency of 5–7 Hz. This is the normal-branch QPO (NBO). The frequency of the NBO stays approximately the same when the source is on the NB. When the source enters the FB, it sometimes remains present, evolving to a higher frequency; this is the so-called flaring-branch QPO (FBO).

GX 17+2 displayed all three branches when it was observed with *EXOSAT* (Hasinger & van der Klis 1989; Langmeier, Hasinger, & Trümper 1990; Kuulkers et al. 1996) and *Ginga* (Penninx et al. 1990). An HBO with an amplitude of 1%–2% (rms) was observed on the HB with frequencies between 18 and 30 Hz. No HBO was seen on the NB. The NBO and FBO were also seen in the appropriate branches. In this

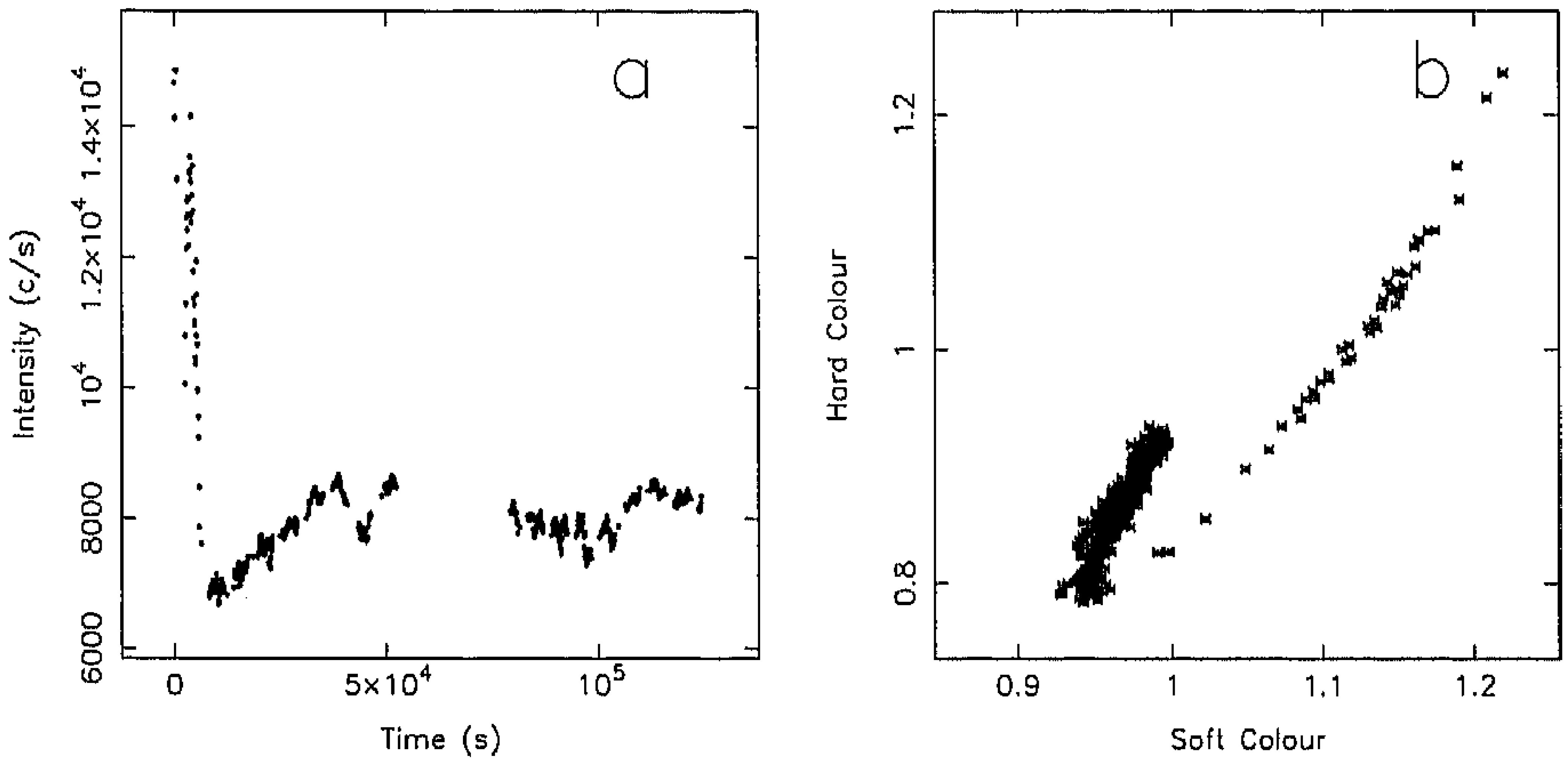

FIG. 1.—(*a*) X-ray light curve and (*b*) X-ray color-color diagram. The count rate in the light curve is taken in the 2.3–19.2 keV energy range. Soft color is the (4.6–7.0 keV)/(2.3–4.6 keV), and hard color the (7.0–19.2 keV)/(4.6–7.0 keV), count-rate ratio. Each data point corresponds to 96 s of data. The error bars are plotted in the figures. Note that in the light curve the error bars are smaller than the points.

Letter, we describe a new QPO phenomenon on the NB that differs in several important respects from the standard picture just sketched.

2. OBSERVATIONS

GX 17+2 was observed with the proportional counter array (PCA) on board the *Rossi X-Ray Timing Explorer* (*RXTE*; see Bradt, Rothschild, & Swank 1993) from 1996 February 7 1320 UT until February 8 0529 UT and from 1996 February 8 1113 UT until February 9 0004 UT. The data were broken up into segments of ~40 minutes because of Earth occultations, passage through the South Atlantic Anomaly, or both. Throughout the entire observation, data were collected in the 2–11.7 keV energy range in 16 energy bands with a time resolution of 2 ms. Data were also recorded simultaneously with 16 s resolution in 129 energy bands covering the 2–60 keV energy range.

3. ANALYSIS AND RESULTS

The 16 s data were used to produce a light curve and an X-ray color-color diagram (Fig. 1). At the beginning of the observation, GX 17+2 was on the flaring branch and count rates ranged up to 15,000 counts s^{-1}. It then made a transition to the normal branch, where it remained for the rest of the observation time. In order to correlate the properties of the rapid X-ray variability with changes in the X-ray spectrum, we used the S_Z (distance along the Z track) parameterization (see Hertz et al. 1992; Dieters & van der Klis 1996). The length of the NB was set to 1.0, with the highest point of the NB in our data assigned the value $S_Z = 1$ and the NB-FB junction assigned $S_Z = 2$. We divided the NB into 10 equal-S_Z segments and calculated an average power spectrum of the 2–11.7 keV high time resolution data corresponding to each segment. The lowest frequency in the power spectrum was 1/16 Hz; the highest frequency was 256 Hz. We used a function composed of a constant (the Poisson level) plus a power law (the low-frequency noise) plus Lorentzian peaks (the HBO and NBO) to fit the power spectra. The fit results (Table 1) were corrected for background and differential dead time (van der Klis 1989).

On the upper normal branch, $S_Z < 1.4$, we see a narrow QPO peak near 60 Hz (Fig. 2), with an FWHM of only ~4.0 Hz and an rms amplitude of 1%–2%. Its frequency increased slightly, from 59 to 62 Hz, when GX 17+2 moved down the NB from $S_Z = 1$ to $S_Z = 1.4$. Between $S_Z = 1.4$ and $S_Z = 1.5$, the frequency decreased to ~55 Hz, and, moving down to $S_Z = 1.6$, it dropped further to ~50 Hz. At the point ($S_Z = 1.4$) at which the frequency reached its maximum, the QPO peak broadened to an FWHM of 10–15 Hz. The amplitude stayed approximately the same along the entire NB, between 1% and 2% (rms). The frequency, FWHM, and rms amplitude of the QPO are plotted versus S_Z in Figure 3. At around $S_Z = 1.8$, the 50–60 Hz QPO disappears. At that point, another QPO has already appeared around 7 Hz, obviously the well-known NBO. Both QPO peaks are simultaneously visible in the power spectrum for S_Z between 1.6 and 1.8. The analysis of the 7 Hz QPO and the noise components will be discussed in a forthcoming paper.

4. DISCUSSION

We have found a QPO around 60 Hz in the X-ray flux of GX 17+2 when this source was on the normal branch. As the source moved from the upper part of the NB downward, the QPO frequency first increased from 59 to 62 Hz and then decreased to ~50 Hz. In the upper part of the NB, the QPO peak was very narrow, ~4 Hz. In the following we argue that this QPO is most likely the horizontal-branch QPO.

TABLE 1

QPO PARAMETERS

S_Z	rms Amplitude (%)	FWHM (Hz)	Frequency (Hz)
1.05 ± 0.05.........	1.7 ± 0.2	10.8 ± 5.3	58.6 ± 1.1
1.15 ± 0.05.........	1.1 ± 0.09	3.6 ± 0.6	60.3 ± 0.2
1.25 ± 0.05.........	1.1 ± 0.1	4.2 ± 1.1	60.6 ± 0.4
1.35 ± 0.05.........	0.9 ± 0.1	3.4 ± 1.6	61.5 ± 0.5
1.45 ± 0.05.........	1.4 ± 0.2	14.8 ± 4.0	56.4 ± 1.5
1.55 ± 0.05.........	1.5 ± 0.1	12.8 ± 2.9	55.7 ± 1.0
1.65 ± 0.05.........	1.6 ± 0.2	16.6 ± 5.3	50.6 ± 2.3
1.75 ± 0.05.........	1.1 ± 0.3	8.8 ± 5.3	51.2 ± 2.3

NOTE.—All errors correspond to $\Delta\chi^2 = 1$. For all fits, χ^2 per degree of freedom is ~1.0.

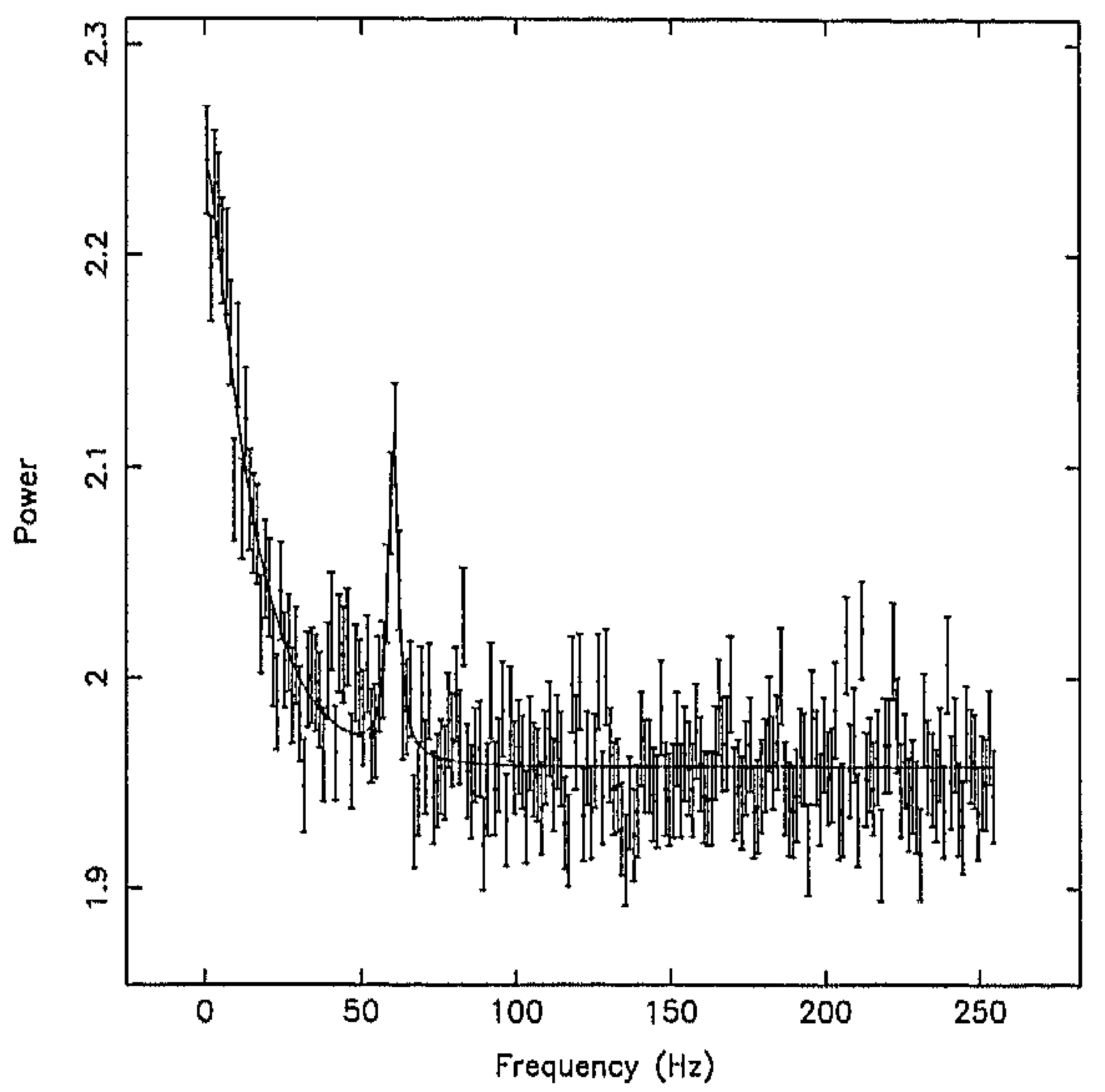

FIG. 2.—Power spectrum in the upper normal branch, between S_Z = 1.1 and S_Z = 1.2, showing the low-frequency noise and the narrow 60 Hz QPO peak. The spectrum is Leahy-normalized. The fit is also plotted.

In the other Z sources in which an HBO is observed on the NB, GX 5−1 (Lewin et al. 1992; Kuulkers et al. 1994), Cygnus X-2 (Wijnands et al. 1996), and GX 340+0 (Kuulkers & van der Klis 1996), we see that the HBO frequency increases when the source moves along the HB to the HB-NB junction, but remains constant at a frequency consistent with that at the junction when the source moves down the NB. In GX 17+2, the HBO had previously only been observed on the HB. With *EXOSAT*, the entire Z was observed (Hasinger & van der Klis 1989; Langmeier et al. 1990; Kuulkers et al. 1996). The HBO was detected on the HB with a frequency that increased from ~24 Hz at the left end of the HB to ~28 Hz halfway across the HB, at which point the HBO disappeared into the noise (Kuulkers et al. 1996). No HBO was found on the NB. However, *EXOSAT* was not sensitive enough to detect in GX 17+2 a QPO as weak as we detected by using *RXTE*. *Ginga* was sensitive enough to detect such a weak QPO, but much of the NB, particularly the upper part and the HB-NB junction, was not seen when GX 17+2 was observed at high time resolution (Penninx et al. 1990). The HBO was detected on the HB and was found to increase in frequency from ~18 Hz at the left of the HB to ~30 Hz at the rightmost part of the HB seen in these observations. It is possible that the right end of the HB and the HB-NB junction were not observed, so that the HBO frequency at the HB-NB junction is higher than ~30 Hz. Thus HBOs on the NB with frequencies near 60 Hz have been found in other Z sources, and previous satellites were either insufficiently sensitive or did not observe at the right moment in the right mode to detect the weak 50–60 Hz QPO that we have found in the NB. In addition, the frequency of the HBO of GX 17+2 at the HB-NB junction has never been measured.

For these reasons, we think that the 50–60 Hz QPO we found in the NB of GX 17+2 is most likely the HBO. If true, then this HBO has a number of new characteristics. On the upper part of the NB, the HBO has a higher frequency and is much more coherent than seen previously. Whereas, for other

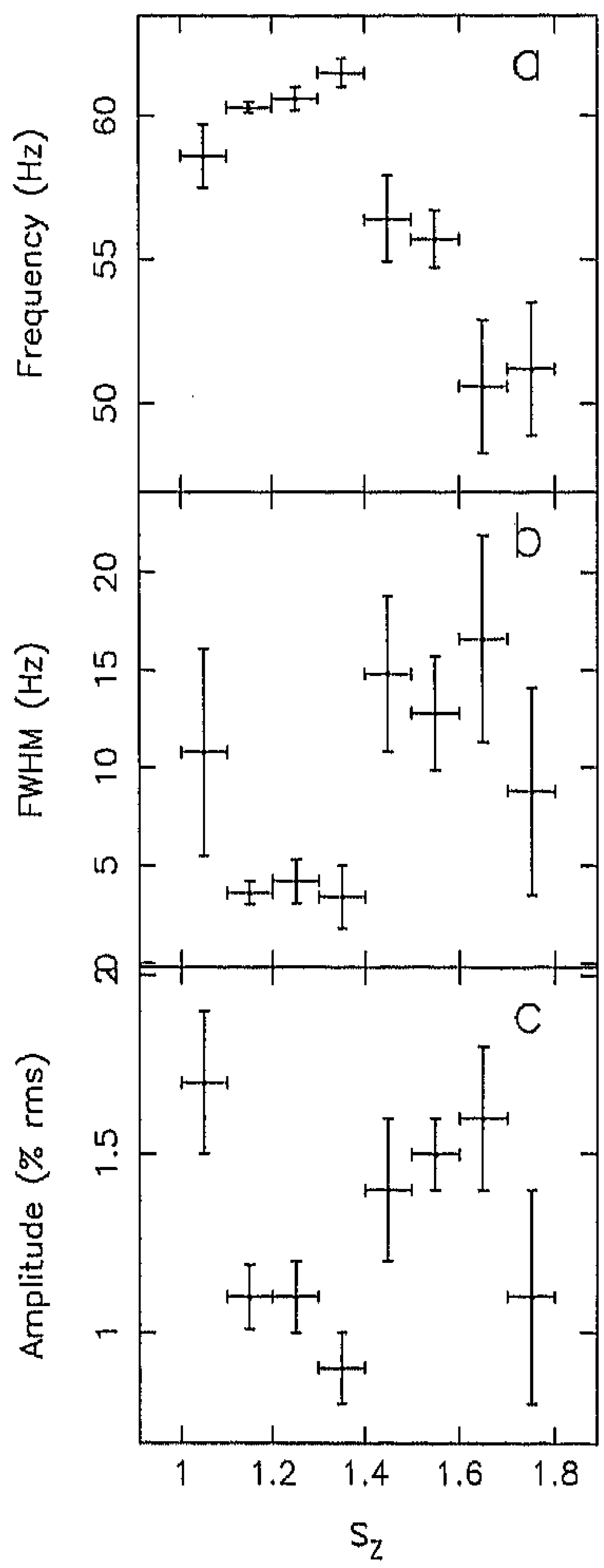

FIG. 3.—QPO properties as function of S_Z-value, showing (*a*) the frequency, (*b*) the FWHM, and (*c*) the rms amplitude of the QPO. Error bars correspond to $\Delta\chi^2 = 1$.

Z sources, the HBO frequency on the NB is consistent with being constant, for GX 17+2 it can be shown for the first time that the frequency of the HBO varies by ~10 Hz. We note that our interpretation can be tested by performing an observation of GX 17+2 moving through the HB-NB junction and observing the frequency variations of the HBO. The HBO frequency should increase along the HB up to ~60 Hz at the HB-NB junction.

A decrease in HBO frequency along the NB, such as we observe between S_Z = 1.4 and 1.6, is not in accordance with the predictions of the beat-frequency model if all the mass flux is through the inner disk, since, under the usual interpretation of the Z track, motion down the NB is thought to be caused by an increase of mass flux onto the neutron star and should therefore produce an increase of the HBO frequency. In the following, we discuss one possible solution to resolve this discrepancy between our interpretation of the data and the beat-frequency model. This solution makes use of a previous proposal (Fortner, Lamb, & Miller 1989) that not all of the mass flux toward the neutron star is by way of a thin disk but part of it accretes instead by way of an approximately radial inflow. In this picture, one is naturally led to find the explanation for the unexpected behavior of the HBO frequency as a function of mass accretion rate in a change in mass flux ratio between disk and radial flow as the source moves down the NB. We note that, although the behavior of the HBO frequency on the NB that we discovered had not been predicted, neither is the introduction of a radial flow in addition to a thin disk entirely ad hoc. The presence of a radial flow was proposed earlier based on the properties of the NBO, which strongly suggest the presence of a Comptonizing medium of variable optical depth (Fortner et al. 1989). The specific behavior of the mass flux as the source moves down the NB that we assume below, however, is suggested only by our specific data and needs additional tests. We shall mention examples of such tests later on.

In the models of Alpar & Shaham (1985) and Lamb et al. (1985), the frequency of the HBO is not determined by the total mass accretion rate $\dot{M}_{NS}$ onto the neutron star (which in the unified model of Z and atoll sources [see Lamb 1989] increases monotonically as a source moves down the NB) but by the accretion rate $\dot{M}_i$ through the inner part of the Keplerian disk to the stellar surface. $\dot{M}_{NS}$ is the sum of $\dot{M}_i$ and the mass flux $\dot{M}_r$ through an approximately radial flow from the inner disk onto the neutron star.

To keep this model consistent with the behavior of the 50–60 Hz QPO found in the present study, we assume that $\dot{M}_{NS}$ onto the neutron star increases down the NB but that, from $S_Z = 1.4$ onward, $\dot{M}_i$ decreases. $\dot{M}_i$ can decrease only if $\dot{M}_r$ increases faster than $\dot{M}_{NS}$ as GX 17+2 moves down the NB. It is uncertain what determines the exact value of $\dot{M}_i/\dot{M}_r$. A significant increase in $\dot{M}_r$ between $S_Z = 1.4$ and $S_Z = 1.6$, when the N/FBO appears, is qualitatively consistent with the unified model (Fortner et al. 1989).

Assuming that the magnetic field of the neutron star at the inner edge of the Keplerian flow is approximately dipolar, we can derive an upper bound on the dipole magnetic moment μ of the neutron star. The inner part of the accretion disk around the neutron star is expected to be radiation pressure–dominated. For such a disk, the beat frequency ν_B is

$$\nu_B = 1.71 \left(\frac{\dot{M}_i}{\dot{M}_E}\right)^{0.225} \left(\frac{M_{NS}}{1\,M_\odot}\right)^{0.695} \times \left(\frac{\mu}{10^{30}\ \mathrm{G\ cm^3}}\right)^{-0.765} - \nu_s\ \mathrm{Hz} \qquad (1)$$

(see Ghosh & Lamb 1992), where ν_s is the spin frequency of the neutron star, $\dot{M}_E$ is the mass flux that would produce the Eddington critical luminosity for accreting matter of cosmic composition, and M_{NS} is the mass of the neutron star. Assuming that $\dot{M}_{NS}$ at $S_Z = 1.8$ is greater than at $S_Z = 1.4$ and that $\dot{M}_r$ is less than 30% of $\dot{M}_{NS}$ (as expected in the unified model; see Fortner et al. 1989), we obtain from equation (1) the inequality

$$\mu < 5\ \ 10^{27} \left(\frac{\nu_{1.4} - \nu_{1.8}}{10\ \mathrm{Hz}}\right)^{-1.3} \times \left(\frac{M_{NS}}{1.4\,M_\odot}\right)^{0.91} \left(\frac{\dot{M}_{1.4}}{\dot{M}_E}\right)^{0.29} \mathrm{G\ cm^3}, \qquad (2)$$

where $\nu_{1.4}$ and $\nu_{1.8}$ are the observed values of the QPO frequency at $S_Z = 1.4$ and $S_Z = 1.8$ and $\dot{M}_{1.4}$ is the total mass flux $\dot{M}_{NS}$ at $S_Z = 1.4$. $\dot{M}_{1.4}/\dot{M}_E$ is expected to be ~0.8 (Psaltis, Lamb, & Miller 1995), so the last factor on the right is close to unity. Using the observed values of $\nu_{1.4}$ and $\nu_{1.8}$ and the relation $B_s^{eq} = \mu/R^3$ between the dipole component of the star's magnetic field at the magnetic equator and the dipole magnetic moment μ and radius R of the star, inequality (2) yields an upper bound of $\sim 5 \times 10^9$ G on B_s^{eq} for $R = 10^6$ cm. This upper bound is consistent with numerical computations of the X-ray spectrum of GX 17+2 (Psaltis et al. 1995). If in subsequent observations the HBO is detected further down the NB and its frequency is found to become even smaller than 51 Hz, the upper bound on the dipole magnetic field of the neutron star can be reduced.

As mentioned earlier, the idea that $\dot{M}_i$ decreases and that $\dot{M}_r$ strongly increases as the source moves down the NB needs observational verification. There are various observable effects of the radial flow on the X-ray spectrum, as well as on the energy dependence of the rapid time variability. In particular, the flow affects the average X-ray spectrum by Comptonization (Psaltis et al. 1995) and produces time lags in the HBO as a result of propagation-time differences. We are currently performing extensive numerical simulations, based on our derived change of $\dot{M}_r$, to predict the X-ray spectral and time-lag behavior of GX 17+2 on the NB. These will be reported in a later paper.

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