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DISCOVERY IN 4U 1636−53 OF TWO SIMULTANEOUS QUASI-PERIODIC OSCILLATIONS NEAR 900 Hz AND 1176 Hz

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ABSTRACT

Using the *Rossi X-Ray Timing Explorer*, we observed the low-mass X-ray binary 4U 1636−53 on 1996 February 28, April 23, and May 29. On February 28, two simultaneous quasi-periodic oscillations (QPOs) occurred at frequencies between 890 and 920 Hz and between 1150 and 1193 Hz. The rms amplitude and FWHM of the lower frequency QPO were 7.3% ± 0.4% and 26 ± 4 Hz, whereas those of the higher frequency QPO were 6.1% ± 0.8% and 64 ± 25 Hz. Averaged over minutes, the FWHM of the lower frequency QPO was sometimes as low as 4 Hz. The rms amplitudes of the QPOs increase with photon energy. The frequency of the lower frequency QPO increases, and its amplitude decreases, with accretion rate as inferred from the position of the source in the X-ray color-color diagram. The frequency difference between the two QPOs is consistent with being constant at 276 ± 10 Hz. The frequency of the higher frequency QPO is the highest so far observed in a low-mass X-ray binary. Assuming that this frequency is the orbital frequency of gas in stable Keplerian orbit around the neutron star, we derive upper limits on the mass and radius of the neutron star of 2.1 $M_\odot$ and 16.5 km. On April 23 we detected no kilohertz QPOs (95% confidence upper limits were typically 3%–5.5% rms in the frequency range 100–2000 Hz). On May 29 we detected a single 853–896 Hz QPO with an amplitude of ∼7% rms that increases with photon energy and decreases with QPO frequency. There was no significant correlation between the frequency of this QPO and the count rate or spectral changes.

Subject headings: accretion, accretion disks — stars: individual (4U 1636−53) — stars: neutron — X-rays: stars

1. INTRODUCTION

Zhang et al. (1996) recently reported the discovery of a single ∼870 Hz quasi-periodic oscillation (QPO) in the low-mass X-ray binary (LMXB) and atoll source (Hasinger & van der Klis 1989; Prins & van der Klis 1996) 4U 1636−53. Kilohertz QPOs have been found so far in the persistent emission of eight LMXBs, two Z sources (Sco X-1: van der Klis et al. 1996a, 1996c; GX 5−1: van der Klis et al. 1996d), and five other atoll sources besides 4U 1636−53 (4U 1728−34: Strohmayer et al. 1996; 4U 1608−52: Berger et al. 1996; 4U 0614+09 [probably an atoll source]: Ford et al. 1997; 4U 1735−44: Wijnands et al. 1996; 4U 1820−30: Smale, Zhang, & White 1996). In the sources Sco X-1, GX 5−1, 4U 1728−34, 4U 0614+09, and 4U 1820−30, two kilohertz QPOs are seen simultaneously; in the others, only one QPO peak has so far been seen at any one time. In this Letter, we report the first detection in 4U 1636−53 of two simultaneous QPOs, at frequencies between 890 and 920 Hz and between 1150 and 1193 Hz. The latter QPO frequency is the highest found so far in any source. Interpretation of this frequency in terms of Keplerian orbital motion would strongly constrain the mass-radius relation of neutron stars. A preliminary announcement of this discovery has already been made by van der Klis et al. (1996b).

2. OBSERVATIONS AND ANALYSIS

We observed 4U 1636−53 on 1996 February 28 0550–0829 UT, on April 23 0124–0333 UT, and on May 29 0114–0247 UT, using the proportional counter array (PCA) on board the *Rossi X-Ray Timing Explorer* (Bradt, Rothschild, & Swank 1993). Earth occultations and South Atlantic Anomaly passages split the data into 2000–3000 s segments. The source count rate varied between 1950 and 2258 counts s^{-1} (2.1–19.1 keV) on February 28, between 2200 and 2400 counts s^{-1} on April 23, and between 1600 and 1850 counts s^{-1} on May 29 (both 2.0–19.0 keV). The background was typically 50 counts s^{-1}. Because of intervening PCA gain changes, the count rates and the colors of the first observation cannot be compared directly with those of the other two. Fitting the spectra with a two-component (blackbody plus power law) model, we derive 2–10 keV fluxes of 4.0×10^{-9}, 4.1×10^{-9}, and 3.2×10^{-9} ergs cm^{-2} s^{-1}, respectively.

Data were collected on February 28 with time resolutions of 16 s (129 photon energy channels covering the range 1–65 keV), 4 ms (four channels: 1–5.8 keV), and 8 μs (eight channels: 5.8–65.5 keV), and on April 23 and May 29 with time resolutions of 16 s (129 channels: 1–98.9 keV) and 8 μs (eight channels: 8.7–98.9 keV). On May 29, data were also collected with time resolutions of 250 μs (one channel: 1–18.3 keV) and 4 ms (four channels: 1–8.7 keV).

We constructed color-color diagrams (CDs) from all 16 s data. For the February 28 observation, we defined the soft and

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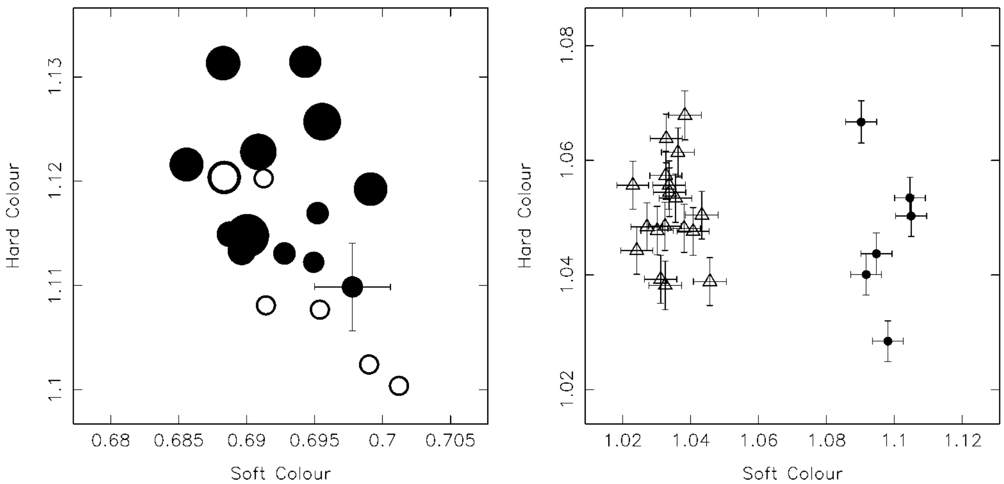

FIG. 1.—Color-color diagrams of the February 28 data (*left*) and the April 23 and May 29 data (*right*). In the left panel, the area of the filled circles indicates the amplitude of the lower frequency QPO. The area of the open circles indicates 95% confidence upper limits on the QPO amplitude. The symbol areas scale linearly with rms amplitude (from 5% to 12%). Typical error bars for the colors are shown. In the right panel, the April 23 data are represented by circles and the May 29 data by triangles. For the definitions of the colors, see § 2. All points are 256 s averages.

hard colors as the (3.7–4.8 keV)/(2.1–3.7 keV) and the (6.9–19.1 keV)/(4.8–6.9 keV) count rate ratios, respectively, and for the April 23 and May 29 observations as the (3.5–4.6 keV)/(2.0–3.5 keV) and the (6.9–19.0 keV)/(4.6–6.9 keV) ratios. The remaining data were used to calculate power spectra, which were fitted with a power law (the very low frequency noise [VLFN], measured between 0.01 and 1 Hz), one or two Lorentzian distributions (the QPOs, if present), and a constant level (the Poisson noise). We corrected the results of the fits for background and differential dead time (see van der Klis 1989). The errors were determined using $\Delta\chi^2 = 1.0$ and the upper limits using $\Delta\chi^2 = 2.71$, which corresponds to the 95% confidence level. The reduced χ^2 values of the fits were all ~1.

3. RESULTS

3.1. *February 28 Observation*

From the CD (Fig. 1, *left*) it is not obvious whether the source was in the banana state or the island state during this observation. The weak VLFN, which had an rms amplitude ranging from 0.7% ± 0.2% at 1 keV to 2.3% ± 0.4% at 19 keV, and the absence of a strong high-frequency noise (HFN) component in the power spectrum indicate (see Prins & van der Klis 1996) that 4U 1636−53 was on the lower part of the banana branch.

When all four data segments (~2000 s each; see § 2) are combined, two highly significant QPOs are seen near 900 and 1176 Hz, both with rms amplitudes of 6%–7% (Fig. 2, *left*; Table 1). No signal was detected at the 276 Hz difference frequency (<2.0% rms) or at the 1453 Hz frequency of the higher frequency QPO plus the difference frequency (<3.0% rms). In the combined data of segments 1 and 2, we detected only the higher frequency QPO; in the data of segment 3, both QPOs; and in all the data of segment 4, only the lower frequency peak (Table 1). During a 4 minute part of segment 4, both QPOs were detected (Table 1). The lower frequency QPO was much broader during this interval than during segment 3 and the rest of segment 4. When two peaks were present, their frequency difference was consistent with being constant at 276 ± 10 Hz. The amplitudes of both QPOs increase with photon energy in the same way (Table 1).

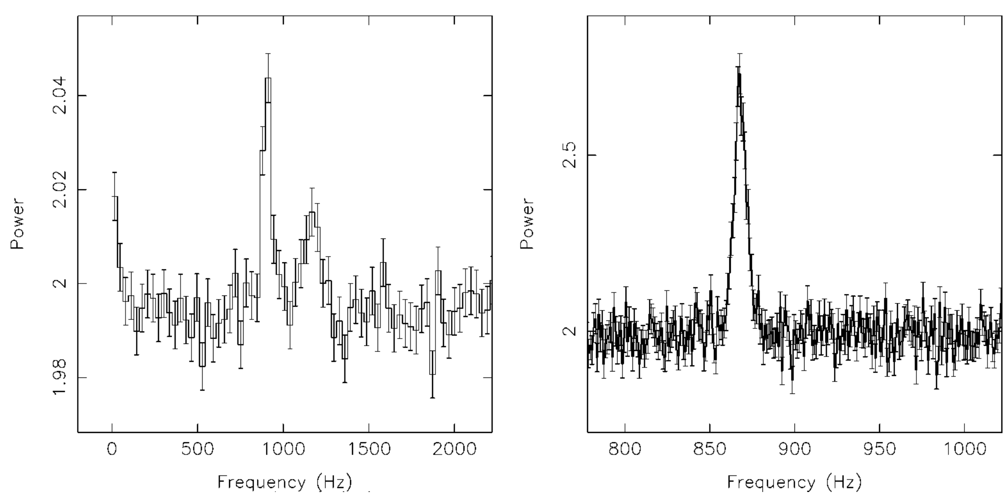

FIG. 2.—Leahy-normalized power spectra of 4U 1636−53. The left panel is for February 28 and shows two kilohertz QPOs. The right panel is from the first 3000 s of the data taken May 29 and shows a single kilohertz QPO. These figures are not corrected for counting statistics or dead time.

TABLE 1

QPO PARAMETERS DURING THE FEBRUARY 28 OBSERVATION

		Lower Frequency QPO			Higher Frequency QPO		
Segment	Energy (keV)	rms Amplitude (%)	FWHM (Hz)	Frequency (Hz)	rms Amplitude (%)	FWHM (Hz)	Frequency (Hz)
All.............	5.8–65.6	7.3 ± 0.4	26 ± 4	899.5 ± 1.5	6.1 ± 0.8	64 ± 25	1176 ± 10
1 + 2..........	5.8–65.6	<5.9	25[a]	921.9 ± 7.7	5.5 ± 0.9[b]	28 ± 13	1193 ± 5
3................	5.8–65.6	8.0 ± 0.5	17 ± 3	897.5 ± 1.0	6.6 ± 1.0[c]	56 ± 36	1147 ± 13
4................	5.8–65.6	8.8 ± 0.7	25 ± 6	901.3 ± 1.9	<7.5	50[a]	1183 ± 15
4[d]..............	5.8–65.6	11.9 ± 2.0	77 ± 37	920 ± 16	8.8 ± 1.3	23 ± 10	1183 ± 4
All.............	5.8–8.5	6.0 ± 1.2	50 ± 36	910 ± 12	5.1 ± 1.6	48 ± 43	1194 ± 19
	8.5–11.7	8.2 ± 1.0	19 ± 11	903.9 ± 3.5	6.8 ± 1.1	50[a]	1183 ± 13
	11.7–25.9	11.9 ± 1.9	22 ± 12	900.3 ± 4.6	11.3 ± 1.2	62 ± 45	1174 ± 17

NOTE.—All errors correspond to $\Delta\chi^2 = 1$. The upper limits correspond to the 95% confidence level.

[a] Parameter fixed.

[b] At a 3.2 σ level.

[c] At a 2.8 σ level.

[d] Only a small part of segment 4: 1996 February 28 0709:38–0713:44 UT.

During segments 1 and 2, the QPOs were not strong enough to detect them in smaller intervals of data, but they were during segments 3 and 4. We divided the latter into 256 s intervals, during which only the very narrow (~5 Hz), lower frequency QPO could be detected. During segment 3, the QPO frequency decreased from 920 to 890 Hz, and during segment 4 from 905 to ~895 Hz. The amplitude of the lower frequency QPO decreased when its frequency increased (Fig. 3, *left*). One point (which corresponds to the 4 minute interval) does not follow this correlation. When the source moved further up the banana branch (from upper left to lower right in Fig. 1, *left*), to higher inferred mass accretion rates ($\dot{M}$), the amplitude of the lower frequency QPO decreased and its frequency increased. No correlation was found between the FWHM (typically ~5 Hz) and the frequency of this QPO or between its frequency and the count rate.

3.2. *April 23 and May 29 Observations*

No strong HFN is present in the April 23 or May 29 power spectra, indicating that 4U 1636−53 was on the banana branch at both times (see Prins & van der Klis 1996). The CD (Fig. 1, *right*) indicates that 4U 1636−53 was further up the banana branch (i.e., $\dot{M}$ was higher) on April 23 than on May 29. This is confirmed by the fact that, in the energy range 10.6–12.4 keV, the VLFN rms amplitude during the April 23 observation (4.0% ± 0.4%) was about twice that during the May 29 observation (2.1% ± 0.4%). The part of the power spectrum below 100 Hz on May 29 is very similar to that on February 28. Both have no strong HFN and similar VLFN. We tentatively suggest that on February 28 and May 29 4U 1636−53 was at about the same point on the banana branch.

On April 23, no QPOs above 100 Hz were detected. The 95% confidence upper limits for QPOs in the 100–2000 Hz range are 3%–5.5% rms (8.7–96.6 keV), depending on FWHM (10–50 Hz). On May 29 we see a very significant QPO at 865 Hz (Fig. 2, *right*), with an amplitude of 7.1% ± 0.3% rms and a typical FWHM of 4–6 Hz when averaged over minutes. The frequency of this peak wandered between 870 and 900 Hz during the observation (see Fig. 4 [Pl. L10]). Dividing the data into 256 s (or 128 s, when rapid changes in frequency occurred) intervals and fitting the power spectra, we find no significant correlation between the frequency and the count rate or position of 4U 1636−53 in the CD. However, no significant motion along the banana branch was detected. The QPO amplitude is anticorrelated with its frequency (Fig. 3, *right*). The QPO rms amplitudes as a function of photon

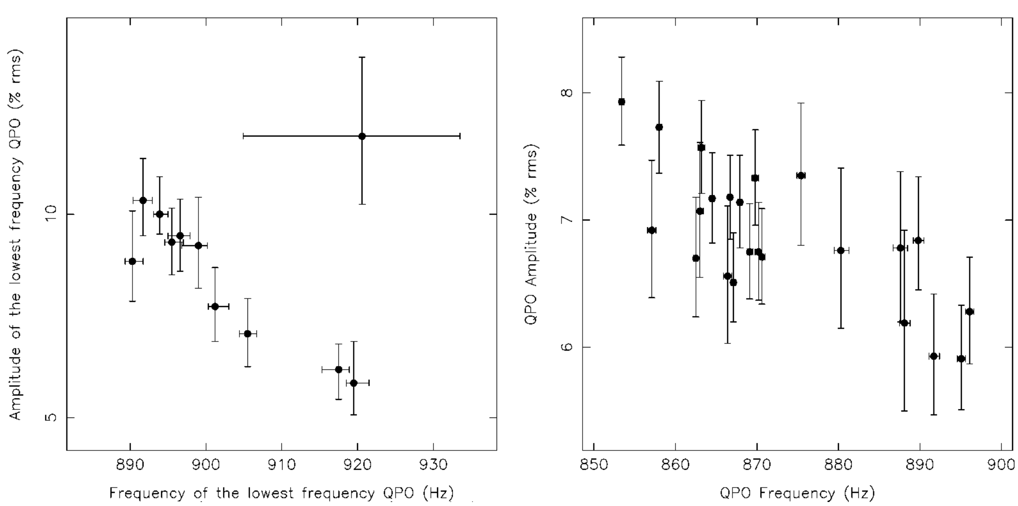

FIG. 3.—Amplitudes of the lower frequency QPO observed on February 28 (*left*) and of the single kilohertz QPO observed on May 29 (*right*) plotted vs. their frequencies. The energy range used was 5.8–65.5 keV on February 28 and 1–18.3 keV on May 29.

energy are 7.1% ± 0.1%, 14.9% ± 0.8%, 15.1% ± 1.3%, 18.3% ± 1.7%, 17.8% ± 3.2%, and 16.0% ± 2.1% at 1–18.3, 8.7–10.6, 10.6–12.4, 12.4–14.6, 14.6–16.8, and 14.6–22.7 keV, respectively. Assuming that the oscillation at 1–8.7 keV is in phase with the oscillation at 8.7–18.3 keV, the rms amplitude of the former is ~5%. Thus the rms amplitude increases from ~4 to ~11 keV, but above that it stays approximately constant.

4. DISCUSSION

We have detected for the first time two simultaneous kilohertz QPOs in 4U 1636−53, at frequencies near 900 Hz and 1176 Hz, during our February 28 observation. The source was then probably on the lower banana branch. Both QPOs disappeared when the source moved further up the banana branch and $\dot{M}$ probably increased. On May 29, when the source was also in the lower banana branch, we found a single ~860 Hz QPO, with properties similar to those found by Zhang et al. (1996).[7] During their observation, the source was probably also on the banana branch, in view of the lack of a strong HFN component in the power spectrum (see their Fig. 1). Their similarities suggest that the single kilohertz QPO observed by Zhang et al. (1996) and our May 29 single kilohertz QPO are the same phenomenon. Because of the gain changes (see § 2), it is not clear whether or not the source was further up the banana branch (at higher $\dot{M}$) on February 28, when two QPO peaks were detected, than on May 29, when only one peak was detected. On April 23 the source was much further up the banana branch, and no QPOs were seen. The amplitude of all the kilohertz QPOs in 4U 1636−53 have about the same dependence on photon energy.

When we compare all atoll sources that show kilohertz QPOs with one another, we see that kilohertz QPOs are observed in both the island state and on the banana branch, but that so far they have displayed different characteristics. In the sources 4U 1728−34 (Strohmayer et al. 1996), 4U 0614+09 (Ford et al. 1997), 4U 1735−44 (Wijnands et al. 1996), and 4U 1820−30 (Smale et al. 1996), kilohertz QPOs have been observed when the sources were in the *island state* (as judged by the low-frequency part of their power spectra or their count rate). In 4U 1728−34, 4U 0614+09, and 4U 1820−30 two peaks are seen, and their frequencies are well correlated with count rate. At low count rates only the higher frequency QPO is observed, but it still fits well on the frequency–count rate relation. So far, the only two sources in which kilohertz QPOs have been seen on the *banana branch* are 4U 1636−53 (Zhang et al. 1996; this Letter) and 4U 1608−52 (Berger et al. 1996). The double QPOs observed in 4U 1636−53 on the lower banana branch are probably the same phenomenon as the QPOs seen in the island state of the other atoll sources, because of their same dependence on inferred $\dot{M}$. The single kilohertz QPOs in 4U 1636−53 and 4U 1608−52 resemble each other in many respects. Both sources have shown a very narrow, single 850–900 Hz QPO. This QPO displays drifts in frequency on timescales of half an hour, which look remarkably similar for both sources (cf., e.g., Fig. 4 with Fig. 2*a* of Berger et al. 1996). The properties of those QPOs are not significantly correlated with count rate or with spectral changes.

On the basis of the observations of kilohertz QPOs made so far, we tentatively conclude that there are differences in the QPO behavior that roughly correlate with source state (i.e., $\dot{M}$). We can neither exclude nor confirm the possibility that the double QPOs usually (but not always) seen in the island state and the single QPO seen so far only in the banana state are caused by different mechanisms.

In a small part of the data, the higher frequency peak is at 1193 ± 5 Hz, which is the highest frequency so far observed for a kilohertz QPO. If the lower frequency QPO is the beat between the higher frequency QPO and the neutron star's spin frequency, as in the sonic point (Miller, Lamb, & Psaltis 1996) and magnetospheric (Strohmayer et al. 1996; Ford et al. 1997) beat-frequency models, then the spin frequency is 276 ± 10 Hz (3.6 ± 0.1 ms). Assuming that the higher frequency QPO is at the orbital frequency of gas in stable Keplerian orbit around the neutron star, as required by these models, it can be used to place upper limits on the mass and radius of the star (Miller et al. 1996). A higher frequency QPO at 1193 Hz and a spin frequency of 276 Hz imply that the star's mass and radius are less than 2.1 $M_{\odot}$ and 16.5 km for a wide range of equations of state (C. Miller 1997, private communication). These limits include the effects of frame dragging.

Note added in manuscript.—After we submitted this Letter, Zhang et al. (1997) reported 581 Hz oscillations in type I bursts in 4U 1636−53, which they interpret as either the fundamental or first overtone of the neutron star's spin frequency. They also reported two simultaneous QPOs with similar peak separation to ours, close to half the burst oscillation frequency.

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[7] The count rates during Zhang et al.'s (1996) observation and our May 29 observation were about the same (1800–1900 counts s^{-1}). The count rates reported by Zhang et al. were too high by a factor of ~2 (W. Zhang 1997, private communication).

REFERENCES

Berger, M., et al. 1996, ApJ, 469, L13
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Ford, E., et al. 1997, ApJ, 475, L123
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Miller, C., Lamb, F. K., & Psaltis, D. 1996, ApJ, submitted (astro-ph/9609157)
Prins, S., & van der Klis, M. 1996, A&A, in press
Smale, A. P., Zhang, W., & White, N. E. 1996, IAU Circ. 6507
Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A., Titarchuk, L., & Day, C. 1996, ApJ, 469, L9
van der Klis, M. 1989, in Timing Neutron Stars, ed. H. Ögelman & E. P. J. van den Heuvel (NATO ASI Ser. C, 262) (Dordrecht: Kluwer), 27
van der Klis, M., Swank, J. H., Zhang, W., Jahoda, K., Morgan, E. H., Lewin, W. H. G., Vaughan, B., & van Paradijs, J. 1996a, ApJ, 469, L1
van der Klis, M., van Paradijs, J., Lewin, W. H. G., Lamb, F. K., Vaughan, B., Kuulkers, E., & Augusteijn, T. 1996b, IAU Circ. 6428
van der Klis, M., et al. 1996c, IAU Circ. 6424
———. 1996d, IAU Circ. 6511
Wijnands, R. A. D., van der Klis, M., van Paradijs, J., Lewin, W. H. G., Lamb, F. K., Vaughan, B., Kuulkers, E., & Augusteijn, T. 1996, IAU Circ. 6447
Zhang, W., Lapidus, I., Swank, J. H., White, N. E., & Titarchuk, L. 1997, IAU Circ. 6541
Zhang, W., Lapidus, I., White, N. E., Titarchuk, L. 1996, ApJ, 469, L17

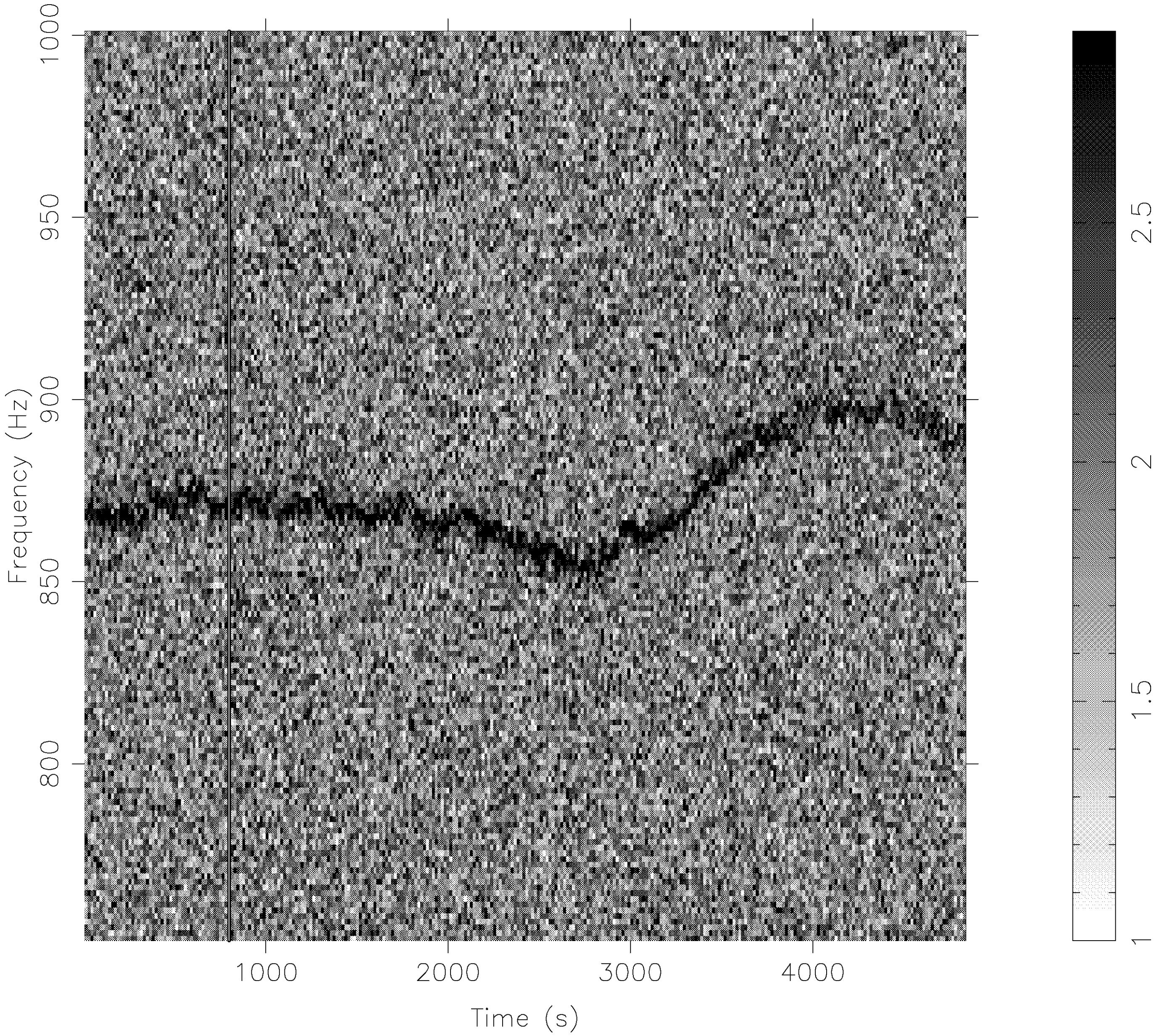

FIG. 4.—Dynamical power density spectrum of the May 29 data. Time is measured from 1996 May 29 0114 UT. A gap near 800 s (*vertical line*) is ignored.

WIJANDS et al. (see 479, L143)