1. INTRODUCTION

Neutron stars in low-mass X-ray binaries (LMXBs) accrete matter from a companion with a mass of less than 1 $M_\odot$ via an accretion disk. In many models, the Keplerian accretion disk is supposed to be terminated at an inner radius $r_{\rm in}$ of a few Schwarzschild radii by, e.g., relativistic effects, radiation drag, or neutron star magnetosphere-disk interactions (see van der Klis 2006 for a review). The motion of the inner disk flow and the geometry of the innermost disk are still uncertain. Observations of correlated behaviors in X-ray spectral and timing variabilities in LMXBs have provided important probes of the accretion-flow dynamics and the stellar-disk interactions.

Kilohertz quasi-periodic oscillations (kHz QPOs, in the frequency range of 200–1300 Hz) have been observed in more than 20 accreting neutron star LMXBs (see van der Klis 2000, 2006 for the recent reviews). Their frequencies are usually considered to be associated with the Keplerian orbital frequency at some preferred radius related to $r_{\rm in}$. Important evidence for the movement of the inner edge of the disk under different mass accretion rates comes from the observation of a positive correlation of frequency versus count rate on timescales of hours to days in some low-luminosity LMXBs, i.e., “atoll” sources (Méndez et al. 1999). A similar correlation (or in some cases an anticorrelation) has also been found in high-luminosity LMXBs, i.e., “Z” sources (Wijnands et al. 1997; Yu et al. 2001; Homan et al. 2002), in the form of the correlations with the curve length $S_2$ along the track traced in an X-ray color-color diagram. The effect of radiation from the surface of the neutron star on the orbital frequency in the accretion disk could have also been observed, e.g., in 4U 1608–52, where Yu & van der Klis (2002) found anticorrelations between the X-ray count rate and the kHz QPO frequency associated with mHz QPO, which was speculated to be due to nuclear burning on the neutron star surface.

Nearly coherent brightness oscillations have been discovered during thermonuclear X-ray bursts in some LMXBs (see Strohmayer & Bildsten 2006 for a review). Recent observations of the accreting millisecond pulsars SAX J1808.4–3658 (Chakrabarty et al. 2003) and XTE J1814–338 (Markwardt et al. 2003c) confirm that the burst oscillation frequency is extremely close to the spin frequency. This supports the interpretation of the burst oscillation in terms of a “hot spot” on the stellar surface (Chakrabarty et al. 2003; Strohmayer & Bildsten 2006), which triggers the efforts to investigate X-ray emission properties on the neutron star surface by folded pulse profiles (Strohmayer et al. 2003; Bhattacharyya et al. 2005; Watts et al. 2005). The best-fitting parameters of the pulsed fraction and the first harmonic can not only determine the compactness of the neutron star, but also help to figure out how the nuclear burning front (the hot spot) propagates on the stellar surface (Bhattacharyya et al. 2005; Watts et al. 2005). However, in the burst-oscillation studies, because of the rather limited photon statistics on the short burst timescale, many similar bursts have to be added to improve the statistics of the folded pulse profiles. The underlying problem is that these bursts may occur with different mass accretion rates. Until now, we knew little about what effects the accretion rate fluctuations can have on the neutron star surface emissions or material depositions.

This situation can be changed with the discovery of the accreting millisecond X-ray pulsars (MXPs; see Wijnands 2006...
for the latest review). Their detectable coherent pulsations allow us to get the pulse profile with good statistics over a long observational period when the energy spectrum (or hardness ratio) varies only slightly. Using a detailed spectroscopic and pulse-profile analysis on SAX J1808.4–3658, Poutanen & Gierliński (2003) constructed a model for X-ray emissions from a hot spot on the surface/boundary layer of a rapidly rotating neutron star in the hard island state. They used it to constrain the compactness of the central star, the position of the emitting region, and the size of the hot spot. Their investigations shed light on further studies of the variations of the surface X-ray emission regions during the evolution of the accretion disk.

Among the seven discovered millisecond X-ray pulsars, XTE J1807–294 is the best candidate for us to investigate the impact of disk flow activities on the neutron star surface emission for four reasons: (1) Along with SAX J1808.4–3658, XTE J1807–294 is a source that has been reported to have twin kHz QPOs4 (Wijnands et al. 2003; Wijnands 2006; Linares et al. 2005). (2) Its binary parameters have been calculated by Campa et al. (2003) and Kirsch et al. (2004) based on the XMM-Newton observations, so we are able to correct the photon arrival times for the orbital motions in producing pulse profiles. (3) The time-averaged energy spectrum of the source is found to be dominated by an optically thin Comptonized component (Falanga et al. 2005), similar to that of SAX J1808.4–3658 (Gierliński et al. 2002), so that we can take the X-ray emission model of SAX J1808.4–3658 as a direct reference. (4) There are no thermonuclear bursts reported in this source; thus, we can focus on studying the effect of disk evolutions. In the six remaining MXPs, i.e., SAX J1808.4–3658, XTE J1751–305, XTE J0929–314, XTE J1814–338, IGR J00291+5934, and HETE J1900.1–2455 (see Wijnands 2006 for a review), the above four conditions cannot be satisfied simultaneously. With the knowledge mentioned above, many basic features of XTE J1807–294 are available as well, such as the shortest orbital period of ~40 minutes and a relatively slow spin frequency of ~191 Hz (Markwardt et al. 2003a). In addition, this source is located 5.7′ away from the Galactic center, with the best known position reported by Markwardt et al. (2003a) based on a Chandra observation. Assuming a distance of 8 kpc, the source luminosity dropped from 1.3 × 10^{37} ergs s^{-1} on 2003 February 28 to 3.6 × 10^{36} ergs s^{-1} on 2003 March 22 (Falanga et al. 2005).

We analyze the evolution of light curves, hardness ratios, pulse profiles, and power density spectra of XTE J1807–294, using \textit{Rossi X-ray Timing Explorer} (\textit{RXTE}) observations from 2003 February 27 to March 31. Our results first show that the positive kHz QPO frequency−count rate correlation on timescales of hours to days is related to some “puffy” flares originating from disk flow inhomogeneities; the behaviors of the pulsed fraction and the first harmonic in the flares are different from those in the nonflares. However, in the whole investigated episode there is a positive correlation between the pulsed fraction and the kHz QPO frequency, which could be the first evidence that neutron star surface emissions are very sensitive to the disk flow inhomogeneities. Furthermore, we describe the \textit{RXTE} observations and data analysis method in § 2, the results of the timing analysis are presented in § 3, and discussions of the results are shown in § 4. Finally, we make a brief conclusion of our studies in § 5.

4 After completion of our paper, we noted that Linares et al. (2005) used the same data on XTE J1807–294 that we analyzed. Our results are similar in kHz QPOs and different in the low-frequency ranges, which might be due to the different choices of the data segments and different data grouping.
Lorentzian's maximum occurs at 
\[ \nu_{\text{max}} = \left( \nu_0^2 + \Delta^2 \right)^{1/2} \]
where \( \nu_{\text{max}} \) is the characteristic frequency, \( \nu_0 \) is the centroid frequency, and \( \Delta \) is the half-width at half-maximum (HWHM) of the Lorentzian. We represent the Lorentzian relative width by \( Q \), defined as \( \nu_0 / 2\Delta \), and the root-mean-square fractional amplitude by rms.

### 3. RESULTS

#### 3.1. Broad Puny Flares in 2003 March

It has been found that the light curve of XTE J1807-294 drops exponentially from February to the end of March of 2003 (Falanga et al. 2005) and then flattens instead of steepening.

![Image of light curve, soft/hard color, fractional amplitude of the pulsation (\( a_0 \)), and the first harmonic component (\( a_1 \)) of XTE J1807-294 in 2003 March. The light curve of 2–30.2 keV is in units of counts s\(^{-1}\) PCU\(^{-1}\) (with time bins of 256 s), the soft color is defined as \( I_{[4.1-7.0\text{ keV}]} / I_{[2.0-4.1\text{ keV}]} \) and the hard color is defined as \( I_{[11.3-38.2\text{ keV}]} / I_{[7.0-11.3\text{ keV}]} \) (with time bins of 16,482 s). The horizontal coordinate stands for the date of the observations, where -1 and 0 denote the days of February 27 and 28, respectively. The four arrows in the fourth panel indicate the positions of the flares.](image_url)
Figure 2.—Hardness intensity diagram of XTE J1807–294. The group numbers for the power density spectra are noted in the top panel.

Figure 3.—Best-fitting parameters of the fractional pulse amplitude \( a_0 \) (top) and the fractional first harmonic amplitude \( a_1 \) (bottom) with respect to the averaged net count rate of the pulse profiles.

much as in SAX J1808.4–3658 (Gilfanov et al. 1998; Gierliński et al. 2002) and XTE J1751–305 (Gierliński & Poutanen 2005). Figure 1 shows that in the former exponentially decaying episode, at least four intensity fluctuations occur, each lasting beyond several thousands of seconds, with small X-ray count rate variations. To make a quantitative analysis, we fit the light curve by an exponential plus multi-Gaussian model. The full width at half-maximum (FWHM) of each Gaussian and the ratio of the magnitude of the Gaussian to the exponential value at the same time are 0.53 days and 7.18/45.42, 0.95 days and 16.8/35.22, 1.67 days and 7.53/20.75, and 0.71 days and 12.33/17.16, respectively. The features of long duration and low amplitude make these fluctuations different from type I thermonuclear bursts and super nuclear outburst (Strohmayer & Brown 2002; Strohmayer & Markwardt 2002) on the neutron star surface. We thus call them “puny” flares for convenience. In the following, it can be noted that these puny flares also feature enhanced soft X-ray emissions and increased pulsed fractions.

The second panel of Figure 1 shows that the soft color drops in the flares, especially at the top of the largest flare of March 14–15. By comparing the light curves in the four energy bands (2.0–4.1, 4.1–7.0, 7.0–13.3, and 13.3–30.2 keV), we find that this is due to the stronger soft X-ray emissions in the 2.0–4.1 keV band. The color-intensity diagram of Figure 2 indicates that except for the puny flares, the soft color decreases with the decay of the outburst, whereas the hard color changes little in the whole investigated episode.

We can deduce from the almost invariant hard color that the hard spectral component changes only slightly in the whole episode. The fitting results of the combined spectra of XMM-Newton, RXTE, and INTEGRAL observations (Falanga et al. 2005) show that hard emissions from the hot and optically thin Comptonized plasma dominate the energy spectra; the contributions of thermal emissions from the accretion disk on February 28 and March 22 are so small that they are almost negligible in the PCA analysis (above 2.5 keV). Therefore, the PCA X-ray emissions can be considered to be mainly generated from the neutron star surface/boundary layer.

3.2. Variations of Pulse Profiles

We fit 86 pulse profiles with a two-component sine function described in § 2. The fitting is good in most cases, with \( \chi^2/\text{dof} \) (degree of freedom) ranging over 32/59–80/59. Situations with \( \chi^2/\text{dof} > 1.3 \) only occur in three pulse profiles. We plot the evolutions of the best-fitting parameters of \( a_0 \) and \( a_1 \) in the fourth and fifth panels of Figure 1, respectively. It can be seen that \( a_0 \) is a more unambiguous indicator of the puny flares than the X-ray intensities and soft colors, not only because of its small errors, but also because \( a_0 \) increases significantly at the top of the flares despite how weak the flare is.

Figure 3 shows the different behaviors of \( a_0 \) and \( a_1 \) with respect to the averaged count rate of the pulse profile. Combining this with the fourth panel of Figure 1, we find that in the normal state, the first harmonic is relatively strong, but it becomes weaker (with \( a_1 \) decreasing from 1.4% to about 0.9%) in the decay of the outburst, whereas \( a_0 \) stays at ~6.5%. In the flares, \( a_0 \) is positively correlated with the averaged count rate, whereas \( a_1 \) is generally at a lower level around 0.7% over the flares. The variational range of \( a_0 \) is ~2%–14%.

3.3. Aperiodic Timing Behavior

We fit the power density spectra by one power-law component plus three to seven Lorentzian components. Errors on the fit parameters are determined using \( \Delta \chi^2 = 1 \). We list the characteristic parameters of the Lorentzians, \( v_{\text{max}}, Q, \) and rms, in Table 2 and the power-law index \( \alpha \) and the \( \chi^2/\text{dof} \) of the fitting in Table 3. In our investigated episode, kHz QPOs have been detected in groups 1–7 and 9–10 and are undetectable in the other groups because of the poor statistics of the power spectra above ~10 Hz. The typical power spectra of XTE J1807–294 are shown in Figure 4, where group 1 is chosen to stand for the nonflare state and group 5 is taken as a representation of the flare state.

We plot the characteristic frequencies of the Lorentzians versus the upper kHz QPO frequency in Figure 5. It shows that XTE J1807–294 has a frequency-frequency correlation similar to that of SAX J1808.4–3658 (van Straten et al. 2005). Most of the Lorentzian components can then be identified in the scheme of Belloni et al. (2002) and van Straaten et al. (2003). In Figure 5, \( L_o \) is the upper kHz QPO; \( L_1 \) is the lower kHz QPO; \( L_{\text{fast}} \) is the hecchertz Lorentzian, a broad Lorentzian with a frequency around 150 Hz; \( L_a \) is the break Lorentzian, a band-limited noise component; and \( L_b \) is the low-frequency Lorentzian just above \( L_a \). It should be noted that when the frequency of \( L_1 \) approaches the range of ~100–150 Hz, it becomes difficult to distinguish from \( L_{\text{fast}} \), especially when one of them is not detected in the spectra, e.g., as in groups 3 and 4 (see Fig. 5). In Table 2 we put a question mark on their identifications.
In Figure 5 we multiply the frequencies of twin kHz QPOs of \( Z \) sources GX 5–1 and GX 17+2 by a factor of 1/1.5 for comparison. Their shifted frequencies are almost consistent with the frequency-frequency distribution of the twin kHz QPOs of XTE J1807–294 (see also Linares et al. 2005). We draw \( \dot{Q} \) versus \( \nu_{\text{max}} \) for both \( L_\text{h} \) and \( L_\text{b} \) in Figure 6. This proves that the frequency shift exists in the upper kHz QPO frequencies in XTE J1807–294, as in the case of SAX J1808.4–3658 (van Straaten et al. 2005).

Besides the five major Lorentzians \( L_\text{h}, L_\text{b}, L_{\text{bmax}}, L_\text{h}, \) and \( L_\text{b} \), the power spectra of XTE J1807–294 present some additional components (Fig. 5). One of the components is the Lorentzian \( L_{\alpha,2} \), with a frequency of nearly double that of \( L_\text{b} \). If \( L_\text{b} \) corresponds to the HBO (horizontal branch oscillation) component of \( Z \) sources (see van der Klis 2006 for a review), \( L_{\alpha,2} \) would correspond to the HBO harmonic. Such a harmonic has never been reported in atoll sources or other accreting millisecond pulsars. Another additional component is the Lorentzian \( L_{\text{LFN}} \), which takes the position of the shifted low-frequency noise (LFN) component of GX 17+2 in the diagram (Fig. 5). The fitted power-law index of \( \nu_{\text{LFN}} \) versus \( \nu_\alpha \) is \( 3.42 \pm 0.29 \), larger than the index of \( \nu_\alpha \) versus \( \nu_\text{g} \) of \( \sim 2.7 \). We use an \( F \)-test to check the probability of the components whose errors are less than 2 \( \sigma \). All of the weak noise components listed in Table 2 have \( F \)-test probabilities less than 0.03.

The simultaneous detection of \( L_\text{h} \) and \( L_{\text{LFN}} \) in XTE J1807–294 makes it evident that \( L_{\text{LFN}} \) is a different component from \( L_\text{b} \). We infer from this finding that the detected LFN in GX 17+2 (Homan et al. 2002) should be a different component from those observed in other \( Z \) sources. The shift factor of about 1.5 in \( L_{\text{LFN}} \) as well as in \( L_\text{h} \) and \( L_\text{b} \) implies that these three components could originate from the same inner disk region.

3.4. Correlations between Count Rate, Pulse Profile, and kHz QPO

We draw in Figure 7 the upper kHz QPO frequency (\( \nu_\text{u} \)) versus the averaged count rate (left) and the fractional pulse amplitude (\( a_0 \)) of the group (right). The averaged count rate and \( a_0 \) of every group were calculated using the same methods described in \( \S \) 3.2.

We can see from Figures 7 and 5 that while the frequencies of the Lorentzians decrease with the count rate in the nonflare state of groups 1–3 and increase with flare intensities in groups 4–6 and 7–10, they do not vary monotonically with the X-ray count rate in the whole episode. The positive frequency–count rate correlations in the rise of the flares seem to be steeper than that measured in the normal outburst decaying state. However, in the whole investigated episode there exists a noticeable positive \( \nu_\text{u} \) versus \( a_0 \) relation with a linear slope coefficient of \( \sim 35 \) (Fig. 7).

4. DISCUSSION

Our motivation for doing a timing analysis on XTE J1807–294 is to probe the effects the disk flow activities have on the neutron star surface X-ray emissions, so we focus on analyzing the variations of pulse profiles and power density spectra during the evolution.

We find several pairs of twin kHz QPOs in the power density spectra of XTE J1807–294, similar to the results of Linares et al. (2005). The frequency separation \( \Delta \nu \) ranges from \( \sim 179 \) to \( \sim 247 \, \text{Hz} \), close to the spin frequency of \( \nu_\text{s} \sim 191 \, \text{Hz} \). Several kHz QPO models, considering the coupling of the neutron star spin to the Keplerian orbit motion of material in the accretion disk, have been put forward to explain this specific feature. We
Note.—In groups 3–4, "—?" is used in the case where $L_t$ can hardly be distinguished from $L_{\text{high}}$.

neutron star or a rotating non-axially-symmetric gravitational potential can provide the coupling; their perturbations on the accretion disk can give rise to very pronounced density fluctuations at the inner edge of the disk. Most recently, Li & Zhang (2005) pointed out an alternative interpretation for the lower kHz QPO in terms of the standing kink modes of magnetic loop oscillations at the inner edge of the disk, where the loops with high-density plasma and small cross section can be produced from the reconnection of the azimuthal magnetic field lines.

The variation of kHz QPO frequencies can be explained by the movement of the inner edge of the accretion disk in the radiative disk truncation model (Miller et al. 1998; van der Klis 2001). For example, the observed positive frequency–count rate correlations on timescales of hours to days in some atoll sources have been interpreted as changes in the inner disk radius due to disk accretion rate fluctuations. We find a similar frequency–count rate correlation in XTE J1807–294, but we note that the shift of the QPO frequency is related to some broad puny flares. The observed frequency–count rate correlation in the rise of the flares seems to be steeper than in the normal state. This result means that (1) in the case of the same count rate, the kHz QPO frequency measured in the rise of the flare is larger than that in the normal state; and (2) for a certain kHz QPO frequency range, the variation of the count rate is smaller in the flare than in the normal state. A possible explanation is that there are blobs of high mass densities at the inner edge of the accretion disk and that they can persist on timescales of hours to days. The formation and the detailed structure of such a kind of blob are still uncertain. We refer to the hydrodynamic simulation result by Pétri (2005)

| Group | Parameter | $L_{\text{LFIN}}$ | $L_{\text{LFN}}$ ($L_{q2}$) | $L_0$ | $L_{\text{fl}}$ | $L_{\text{QPO}}$ | $L_{\text{high}}$ | $L_t$ | $L_u$ |
|-------|-----------|----------------|----------------------|------|-------------|------------|-------------|------|------|
| 1      | $v_{\text{max}}$ (Hz) | 1.93 ± 0.45 | 6.60 ± 0.71 | 24.7 ± 1.0 | 64 ± 14 | 240 ± 33 | 460.4 ± 2.5 |
| 2      | $Q$ | 0.72 ± 0.40 | 0.84 ± 0.23 | 1.37 ± 0.25 | 0.76 ± 0.45 | 1.27 ± 0.67 | 6.9 ± 0.7 |
| 3      | $Q$ | 4.5 ± 1.1 | 8.0 ± 1.0 | 11.2 ± 3.3 | 10.6 ± 2.5 | 10.6 ± 2.5 | 13.5 ± 1.1 |
| 4      | $Q$ | 3.26 ± 0.82 | 17.8 ± 2.4 | 122 ± 44 | 62 ± 18 | 3 ± 1 | 7 ± 1 |
| 5      | $Q$ | 0.64 ± 0.21 | 0.47 ± 0.14 | 0.98 ± 0.26 | 0.98 ± 0.26 | 0.98 ± 0.26 | 1.9 ± 0.4 |
| 6      | $Q$ | 6.24 ± 1.3 | 14.7 ± 1.9 | 205 ± 52 | 104 ± 9 | 10.5 ± 0.7 |
| 7      | $Q$ | 0.49 ± 0.15 | 13.8 ± 3.4 | 2.61 ± 0.9 | 0.68 ± 0.3 | 0.9 ± 0.2 | 3.6 ± 0.8 |
| 8      | $Q$ | 1.9 ± 1.3 | 2.8 ± 1.5 | 5.6 ± 1.7 | 10.9 ± 3.3 | 11.8 ± 3.3 | 7 ± 1.5 |
| 9      | $Q$ | 1.68 ± 0.06 | 3.66 ± 0.29 | 11.9 ± 2.6 | 39.2 ± 12 | 165 ± 26 | 360 ± 11 | 545.3 ± 2.1 |
| 10     | $Q$ | 4.7 ± 1.1 | 3.6 ± 3.7 | 0.42 ± 0.19 | 2.24 ± 0.6 | 0.69 ± 0.05 | 4 ± 1.6 | 13.5 ± 1.1 |
| 11     | $Q$ | 0.25 ± 0.9 | 2.5 ± 1.5 | 9.0 ± 1.4 | 9.8 ± 4.5 | 9.1 ± 2.3 | 10.4 ± 1.9 |
| 12     | $Q$ | 0.38 ± 0.09 | 0.90 ± 0.16 | 0.9 ± 0.25 | 0.9 ± 0.25 | 0.9 ± 0.25 | 6.6 ± 1.1 |
| 13     | $Q$ | 9.9 ± 1.1 | 9.9 ± 1.1 | 9.9 ± 1.1 | 9.9 ± 1.1 | 9.9 ± 1.1 | 9.9 ± 1.1 |
| 14     | $Q$ | 0.85 ± 0.28 | 0.85 ± 0.28 | 0.85 ± 0.28 | 0.85 ± 0.28 | 0.85 ± 0.28 | 0.85 ± 0.28 |
| 15     | $Q$ | 0.37 ± 0.08 | 0.37 ± 0.08 | 0.37 ± 0.08 | 0.37 ± 0.08 | 0.37 ± 0.08 | 0.37 ± 0.08 |
| 16     | $Q$ | 1.1 ± 1.1 | 1.1 ± 1.1 | 1.1 ± 1.1 | 1.1 ± 1.1 | 1.1 ± 1.1 | 1.1 ± 1.1 |
| 17     | $Q$ | 9.0 ± 2.5 | 39.0 ± 2.5 | 39.0 ± 2.5 | 39.0 ± 2.5 | 39.0 ± 2.5 | 39.0 ± 2.5 |
| 18     | $Q$ | 0.40 ± 0.22 | 2.63 ± 1.7 | 0.79 ± 0.07 | 10.8 ± 1.6 |
| 19     | $Q$ | 10.7 ± 2.4 | 6.9 ± 2.8 | 14.9 ± 3.5 | 8.5 ± 4.1 |
| 20     | $Q$ | 4.97 ± 0.82 | 19.2 ± 2.3 | 368 ± 32 | 368 ± 32 |
| 21     | $Q$ | 0.00 (fixed) | 0.00 ± 0.00 | 0.95 ± 0.31 | 0.95 ± 0.31 |
| 22     | $Q$ | 12.9 ± 1.5 | 9.2 ± 1.9 | 16.6 ± 1.3 |

Table 3
Fitted Power-Law Index Together with $\chi^2$ and Degrees of Freedom of the Fitting

| Group | $\alpha$ | $\chi^2$ | dof |
|-------|---------|----------|-----|
| 1      | −2.04 ± 0.16 | 216 | 189 |
| 2      | −1.99 ± 0.08 | 214 | 204 |
| 3      | −1.78 ± 0.09 | 208 | 195 |
| 4      | −1.86 ± 0.14 | 408 | 232 |
| 5      | −1.74 ± 0.18 | 221 | 229 |
| 6      | −1.90 ± 0.06 | 397 | 228 |
| 7      | −1.73 ± 0.09 | 289 | 238 |
| 8      | −1.95 ± 0.21 | 261 | 226 |
| 9      | −2.34 ± 0.16 | 343 | 203 |
| 10     | −1.94 ± 0.15 | 267 | 239 |
Fig. 6.—Plot of the $Q$-values of $L_x$ (left) and $L_b$ (right) of XTE J1807–294 (triangles) vs. the corresponding characteristic frequencies. Data points of SAX J1808.4–3658 (van Straaten et al. 2005) are plotted with gray squares for comparison. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 7.—Characteristic frequencies of the upper kHz QPOs vs. the averaged count rate (left) and the fractional pulse amplitude $a_0$ (right) of groups 1–7 and 9–10. The group numbers are noted in the right panel.
mentioned in the above paragraph, for instance. It might be expected that the intensity of the flares relative to the nearby normal state could be a measure of the mass density of the blob, while the limited time intervals of the flares could be related to the sizes of the blobs. However, besides the variation of mass accretion rate due to accreting the blobs, there are other mechanisms that can influence the X-ray intensity and kHz QPO frequency, such as nuclear burning on the neutron star surface (Zhang et al. 1998; Yu et al. 1999; Yu & van der Klis 2002). To make a further quantitative investigation of the blobs from the observations, we have to first distinguish their different effects.

Accreting inhomogeneous flow as one of the possible origins of flares has been suggested by Moon et al. (2003) for LMC X-4. In the “broad flare” of LMC X-4, the spectrum is softened and the pulse profile becomes simple sinusoids. These features are also observed in the broad puny flare of XTE J1807−294. In the massive X-ray binary LMC X-4, the X-ray emission mechanisms of the magnetic neutron star (with surface magnetic field strength $B \sim 10^{12}$ G) are too complex to be modeled. However, the spectrum of XTE J1807−294 can be well fitted by an absorbed blackbody plus Comptonization model; thus, we can hope to learn more about the X-ray emission properties by fitting the pulse profiles of XTE J1807−294, as done by Gierliński et al. (2002) and Gierliński & Poutanen (2005) for SAX J1808.4−3658 and XTE J1751−305.

Our preliminary results of the pulse-profile analysis show that both $a_0$ and $a_1$ behave differently in the flares and in the non-flares. As for the latter case, while the X-ray count rate decreases, $a_0$ stays at about 6.5%, whereas $a_1$ decreases from ~1.4% to ~0.9%. However, in the former case, $a_1$ is generally at a low level of 0.7%, whereas $a_0$ increases with the flare intensities. The value of $a_0$ spans the range of ~2%−14%, comparable to those observed in some thermoelectronic bursts of XTE J1814−338 (Strohmayer et al. 2003; Watts et al. 2005) and some nonpulsing LMXBs (Muno et al. 2002). According to the X-ray emission model of Poutanen & Gierliński (2003), the variation of the pulse profile can be determined by the changes of the surface-emission parameters, such as the hot spot size, position, and even emission patterns, e.g., the optical depths of the blackbody emission and the Comptonization, respectively. We will present a detailed spectroscopic and pulse-profile modeling analysis in a future work. According to this model, the above results have already shown that the accretion emissions at the neutron star surface/boundary layer are very sensitive to the accretion flow inhomogeneities. The most direct evidence is the observed positive correlation between the kHz QPO frequency and $a_0$ in the investigated episode.

Although we infer from the above results that the broad puny flares could be mainly due to accreting blobs, we cannot exclude the possibility of the existence of some special mode of nuclear burning on the neutron star surface. Bildsten (1993) first proposed that a time-dependent nuclear burning (slow fires) on patches of the neutron star surface can occur in an intermediate accretion regime, where the accretion rate is sub-Eddington but is still too high to allow a type I thermonuclear burst, e.g., $5 \times 10^{-10} M_\odot$ yr$^{-1} < M < 10^{-8} M_\odot$ yr$^{-1}$ for a pure helium-burning case (Bildsten 1995). For XTE J1807−294, the conditions for slow fires seem to be satisfied qualitatively: no type I thermonuclear burst has been observed, and the source luminosity drops from $1.3 \times 10^{37}$ to about $3.6 \times 10^{36}$ ergs s$^{-1}$ (assuming a distance of 8 kpc) in the investigated episode (Falanga et al. 2005). However, the properties of the companion star are still uncertain. It could be a He dwarf with a low inclination angle ($i < 30^\circ$) located at ~8 kpc or a C/O dwarf with a high inclination angle ($60^\circ < i < 83^\circ$) at about 3 kpc (Falanga et al. 2005), which makes it difficult to give a quantitative estimation of the ignition and the spreading of the fires on XTE J1807−294. However, the observations of the low-level luminosity variations on time-scales of $10^4$ s and the possible existence of the very low frequency noise (VLFN) in the mHz−Hz range are all consistent with the features of the slow fires predicted by the theoretical investigations of Bildsten (1995). If the slow fires exist, the position and the size of the blackbody radiation on the neutron star surface will certainly be influenced, making impacts on the soft-band pulse profiles and time lags. We will consider this effect in another work.

5. SUMMARY AND CONCLUSION

XTE J1807−294 shows significant variations of pulse profiles and kHz QPO frequencies during the source evolution in 2003 March. It thus provides a good chance to probe the neutron star surface/boundary layer X-ray emissions, the inner disk flow activities, and their correlations.

The main results we get from the RXTE data analysis are related to some specific “puny” flares, featuring low-amplitude intensity fluctuations, an hours to days long timescale, stronger soft emissions, and a significant increase of fractional pulse amplitude with the flare intensities. A positive kHz QPO frequency−count rate correlation is also found to be connected with the flares: the correlation seems to be steeper in the rise of the flares than in the normal state. However, in the whole investigated episode, the kHz QPO frequency is positively correlated with the fractional pulse amplitude. In the normal state, the fractional pulse amplitude stays constant, and the first harmonic content decreases with the outburst decay.

We propose that accreting high-mass-density blobs could be responsible for all of the above features of the puny flares and conclude that neutron star surface emissions should be very sensitive to the disk flow inhomogeneities in the hard state. Since the variation of the fractional pulse amplitude in the flare is comparable to that in the thermonuclear burst, the effect of the accretion flow inhomogeneity on material depositions at the neutron star surface should be carefully considered in the study of thermonuclear burst oscillations.

Detailed spectroscopic and pulse-profile analysis on XTE J1807−294 will be done to determine the physical parameters of the surface/boundary layer emissions in the whole investigated episode in a subsequent work.

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