DISCOVERY OF A SOFT SPECTRAL COMPONENT AND TRANSIENT 22.7 SECOND QUASI-PERIODIC OSCILLATIONS OF SAX J2103.5+4545

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ABSTRACT

*RXTE* observed SAX J2103.5+4545 on 2003 January 6, while the *Rossi X-Ray Timing Explorer* (*RXTE*) was also monitoring the source. Using the *RXTE* Proportional Counter Array data set between 2002 December 3 and 2003 January 29, the spin period and average spin-up rate during the *XMM-Newton* observations were found to be $354.7940 \pm 0.0008$ s and $(7.4 \pm 0.9) \times 10^{-13}$ Hz s$^{-1}$, respectively. In the power spectrum of the 0.9–11 keV *RXTE* PN light curve, we found quasi-periodic oscillations (QPOs) around 0.044 Hz (22.7 s) with an rms fractional amplitude of $\sim$6.6%. We interpreted this QPO feature as the Keplerian motion of inhomogeneities through the inner disk. In the X-ray spectrum, in addition to the power-law component with high-energy cutoff and the $\sim$6.4 keV fluorescent iron emission line, we discovered a soft component consistent with blackbody emission with $kT \sim 1.9$ keV. The pulse phase spectroscopy of the source revealed that the blackbody flux peaked at the peak of the pulse with an emission radius of $\sim 0.3$ km, suggesting the polar cap on the neutron star surface as the source of the blackbody emission. The flux of the iron emission line at $\sim 6.42$ keV was shown to peak at the off-pulse phase, supporting the idea that this feature arises from fluorescent emission of the circumstellar material around the neutron star rather than the hot region in the vicinity of the neutron star polar cap.

Subject headings: stars: individual (SAX J2103.5+4545) — stars: neutron — X-rays: binaries — X-rays: stars

1. INTRODUCTION

The transient X-ray source SAX J2103.5+4545 was discovered by the Wide-Field Camera on the *BeppoSAX* X-ray observatory during its outburst between 1997 February and September with 358.61 s pulsations and a spectrum consistent with an absorbed–power law model with a photon index of $\sim 1.27$ and an absorption column density of $\sim 3.1 \times 10^{22}$ cm$^{-2}$ (Hulleman et al. 1998). After detection of another outburst in 1999 November by the all-sky monitor on the *Rossi X-Ray Timing Explorer* (*RXTE*), the source was found to be active for more than a year and was continuously monitored through regular pointed *RXTE* observations. Using pulse arrival times, the orbital period and eccentricity of the orbit were found to be 12.68(25) days and 0.4(2), respectively (Baykal et al. 2000a, 2000b). In the timing analysis, the source was initially found to be spinning up for $\sim 150$ days, at which point the flux dropped quickly by a factor of $\sim 7$ and a weak spin-down began afterward (Baykal et al. 2002). The strong correlation between X-ray flux and spin-up rate was explained by using the Ghosh & Lamb (1979) accretion disk model. The X-ray spectra fitted well an absorbed–power law model with a high-energy cutoff and a $\sim 6.4$ keV fluorescent emission line (Baykal et al. 2002).

Orbital parameters found by using *RXTE* observations of the source (Baykal et al. 2000a, 2000b) indicated that the source has a high-mass companion. Hulleman et al. (1998) pointed out a B8-type star within the *BeppoSAX* error box, but its distance ($\sim 0.7$ kpc) implied a luminosity too low to explain the spin-up that was seen in the *RXTE* observations. Recently, a possible candidate for an optical companion of SAX J2103.5+4545 with a visual magnitude of 14.2 was discovered (Reig & Mavromatakis 2003).

SAX J2103.5+4545 was also observed with the *INTEGRAL* observatory in the 3–200 keV band, with significant detection up to $\sim 100$ keV (Lutovinov et al. 2003). The spectral parameters found in the *INTEGRAL* observations of the source were found to be compatible with those found by Baykal et al. (2002).

Since the beginning of the most recent outburst in 2002 June, SAX J2103.5+4545 has been monitored continuously by *RXTE* through regular pointed observations. It was possible to obtain some simultaneous coverage with the *XMM-Newton* observatory on 2003 January 6. The observation of *XMM-Newton* revealed a soft spectral component of the source that was well represented by a blackbody model. This spectral model was verified by simultaneous fitting of the 2003 January 6 *RXTE* Proportional Counter Array (PCA) observation. Using the *XMM-Newton* data set, we also discovered $\sim 22.7$ s quasi-periodic oscillations (QPOs) of this source for the first time. In this paper we present our spectral and timing results of the analysis of the *RXTE* and *XMM-Newton* data sets of SAX J2103.5+4545.

2. OBSERVATIONS

2.1. RXTE

We analyzed the *RXTE* observations of SAX J2103.5+4545 between 2002 December 3 and 2003 January 29, with a total observation time of $\sim 52$ ks. This set of observations is a subset of the *RXTE* observations for proposal number 70082. The
results presented here are based on data collected with the PCA (Jahoda et al. 1996). The PCA instrument consists of an array of five proportional counters (PCUs) operating in the 2–60 keV energy range, with a total effective area of approximately 6250 cm² and a field of view of ~1° FWHM. Although the number of active PCUs varied between two and five during the observations, our observations belong to the epoch for which the background level for one of the PCUs (PCU0) was increased because that PCU started to operate without a propane layer. The latest combined background models were used together with FTOOLS, version 5.2, to estimate the appropriate background.

2.2. XMM-Newton

The XMM-Newton observations took place on 2003 January 6, with an 8.7 ks continuous exposure. Among the three EPIC detectors (Turner et al. 2001; Strüder et al. 2001), the MOS1 and MOS2 detectors were configured in fast uncompressed mode, while the PN was configured in fast timing mode. Data collected by the EPIC detectors on XMM-Newton were processed using version 5.4.1 of the XMM-Newton Science Analysis System. We did not include the data collected by the two Reflection Grating Spectrometers in the data analysis since the count rates from these spectrometers were too low.

3. DATA ANALYSIS

3.1. Pulse Timing and Pulse Profiles

In the timing analysis, we corrected the background-subtracted light curves of the RXTE data to the barycenter of solar system. The data were also corrected for the orbit model using the eccentric orbital parameters given by Baykal et al. (2000b), with the new orbital epoch being MJD 52,633.90 ± 0.05. In order to estimate the pulse frequency and pulse frequency derivative accurately, we used an ~57.5 day time span of RXTE observations between MJD 52,611.48 and MJD 52,668.90, which covers an ~8.7 ks short observation of XMM-Newton data starting at MJD 52,645.85. We obtained the nominal pulse frequency by using a Fourier transform and constructed 20 pulse profiles (one pulse profile for each RXTE orbit) by folding the light curve at this nominal pulse period. We found the pulse arrival times (phase offsets) by cross-correlating these pulse profiles with a template chosen as the most statistically significant pulse profile. In the pulse timing analysis, we used the harmonic representation of the pulse profiles (Deeter & Boynton 1985). In this technique, the pulse profiles are expressed in terms of a harmonic series and cross-correlated with the template pulse profile. The pulse phase offsets can be found from a Taylor expansion,

\[ \delta \phi = \delta \phi_0 + \delta \nu (t - t_0) \frac{1}{2} \dot{\nu} (t - t_0)^2, \]

where \( \delta \phi \) is the pulse phase offset deduced from the pulse timing analysis, \( t_0 \) is the midtime of the observation, \( \delta \phi_0 \) is the phase offset at \( t_0 \), \( \delta \nu \) is the deviation from the mean pulse frequency (or additive correction to the pulse frequency), and \( \dot{\nu} \) is the pulsar’s pulse frequency derivative. We fitted the phase offsets to the Taylor expansion. From the fit, we found the pulse period corresponding to the XMM-Newton observation to be 354.7940 ± 0.0008 s and the 57.5 day average spin-up rate to be (7.4 ± 0.9) × 10⁻¹³ Hz s⁻¹. We did not see any significant timing noise in the residuals of the arrival times, which indicated that the spin-up rate was stable through the observations.

The average 3–20 keV flux of the RXTE observations was (5.5 ± 0.5) × 10⁻¹⁰ ergs⁻¹ cm⁻². The mean spin-up rate and the average X-ray flux were found to be consistent with the previously observed spin-up rate and X-ray flux correlations during the 1999 outburst (see Fig. 7 in Baykal et al. 2002). Detailed timing noise analysis of RXTE observations is in progress and is not in the scope of this paper (A. Baykal et al. 2004, in preparation).

In Figure 1 we present energy-dependent pulse profiles of XMM-Newton EPIC PN data. The feature peaking at the phase ~0.25 before the peak of the main pulse is a prominent feature of the pulse profile. The pulse fraction is 50.9% ± 0.3% at 0.9–11 keV, whereas it is found to be slightly variable in the energy intervals shown in Figure 1, with a minimum of 48.5% ± 0.8% at 7.5–11 keV and a maximum of 53.6% ± 0.7% at 2.5–5.0 keV.

3.2. Transient 22.7 s QPO

In the power spectra of the 0.9–11 keV EPIC PN light curve, we found QPOs around 0.044 Hz (see Fig. 2). In order to test the significance of these oscillations, we averaged nine power spectra and rebinned the frequencies by a factor of 8. Then we modeled the continuum power spectrum with a broken–power law model with a break value of (4.45 ± 0.16) × 10⁻² Hz and power indices of −0.34 ± 0.08 and −2.14 ± 0.05. We modeled the transient oscillations with a Lorentzian centered at (4.40 ± 0.12) × 10⁻² Hz, with a FWHM of (6.1 ± 2.0) × 10⁻³ Hz.

To test the significance of this QPO feature, we normalized the power spectrum by dividing it by the continuum, and we multiplied this result by 2 (van der Klis 1989). The resulting power spectrum would be consistent with a Poisson distribution for 2 × 8 × 9 = 144 degrees of freedom ( dof ). As seen from Figure 2 (bottom), there is a prominent peak at ~0.044 Hz,
with a minimum of excess power (including the error of power) of 3.62, giving a total power of $3.62 \times 8 \times 9 = 260.64$. This gives the probability of detecting a false signal $Q(260.64|144) = 9.39 \times 10^{-9}$. Since we have 512 frequencies in each power spectra, the total probability of having a false signal becomes $9 \times 512 \times 9.39 \times 10^{-9} = 4.3 \times 10^{-5}$. Therefore, the significance of transient oscillations is $1 - 4.3 \times 10^{-5} = 0.999996$, which is consistent with a more than 6 σ level detection. The rms fractional amplitude associated with this QPO feature was found to be $6.6\% \pm 1.9\%$.

We searched transient oscillations using the RXTE PCA light curves in the 3–20 keV energy range; however, we did not see any significant transient oscillations. Then, we extracted a $\sim 50\%$ portion of the overall XMM-Newton EPIC PN light curve at the 3–10 keV energy range that coincided exactly with the $\sim 4.5$ ks part of the RXTE PCA light curve on 2003 January 6 and performed a power spectral analysis. We found that the significances of the 0.044 Hz oscillations for the RXTE and XMM-Newton light curves are 2.5 and 2.8 σ, respectively. We concluded that either the QPO feature originated mostly from a soft component of the spectrum, or it was highly transient. Future observations are required to confirm these oscillations.

### 3.3. Spectral Analysis

We fitted the overall background-subtracted 1–10 keV spectra of PN, MOS1, and MOS2 to an absorbed–power law model (Morrison & McCammon 1983) with a high-energy cutoff (White et al. 1983). In addition, an iron-line feature at 6.42 keV was required in the spectral model (case 1 in Table 1). However, this model did not fit the spectrum of the source well, giving a reduced $\chi^2$ of 2.69. Adding an additional blackbody component to the model decreased the reduced $\chi^2$ to 1.23 (case 2 in Table 1). A joint fit including the PCA data on 2003 January 6 and adding 2% systematic errors (see Wilms et al. 1999; Coburn et al. 2000) was possible with this model, with a reduced $\chi^2$ of 1.1 (case 3 in Table 1 and Fig. 3). Using case 3 (i.e., the joint fit to the model including a blackbody component), the 1–20 keV unabsorbed flux was found to be

![Figure 2](image-url)  
**Fig. 2.—Top:** Power spectrum obtained from the 0.9–11.0 keV EPIC PN light curve and rebinned by a factor of 4. The QPO feature centered at 0.044 Hz is the prominent feature of the power spectrum. **Bottom:** Power spectrum rebinned by a factor of 8, multiplied by 2, and divided by the continuum fit consisting of a broken–power law model with the power indices $-0.34 \pm 0.08$ and $-2.14 \pm 0.05$. Applying the method discussed by van der Klis (1989), the significance of the QPO feature was calculated to be at more than the 6 σ confidence level using the value of the peak at $\sim 0.044$ Hz as shown in this plot.

### Table 1

**Spectral Models of SAX J2103.5+4545**

| Parameter                              | Case 1       | Case 2       | Case 3       | Case 4       |
|----------------------------------------|--------------|--------------|--------------|--------------|
| Multiplication Factors:                |              |              |              |              |
| MOS1                                   | 0.77 ± 0.01  | 0.76 ± 0.01  | 0.76 ± 0.01  | ...          |
| MOS2                                   | 0.76 ± 0.01  | 0.75 ± 0.01  | 0.75 ± 0.01  | ...          |
| PCA                                    | ...          | ...          | ...          | ...          |
| $n_T$ (10^{-22} cm^{-2})               | 0.90 ± 0.02  | 0.68 ± 0.01  | 0.66 ± 0.02  | 2.98 ± 0.14  |
| Iron-line energy (keV)                 | 6.41 ± 0.04  | 6.42 ± 0.02  | 6.42 ± 0.02  | 6.36 ± 0.06  |
| Iron-line $\sigma$ (keV)               | 0 (fixed)    | 0 (fixed)    | 0 (fixed)    | 0.68 ± 0.13  |
| Iron-line equivalent width (eV)        | 48.0 ± 7.0   | 37.1 ± 5.3   | 36.5 ± 5.0   | 107 ± 15     |
| Iron-line flux (ergs s^{-1} cm^{-2})   | (1.69 ± 0.24) × 10^{-12} | (1.37 ± 0.20) × 10^{-12} | (1.36 ± 0.19) × 10^{-12} | (5.14 ± 0.72) × 10^{-12} |
| Iron-line normalization (photons cm^{-2} s^{-1}) | (1.65 ± 0.24) × 10^{-4} | (1.33 ± 0.19) × 10^{-4} | (1.32 ± 0.18) × 10^{-4} | (5.00 ± 0.70) × 10^{-4} |
| Blackbody $kT$ (keV)                   | ...          | 1.91 ± 0.04  | 1.88 ± 0.02  | ...          |
| Blackbody normalization (km^2 (10 kpc)^{-2}) | ...          | 0.88 ± 0.04  | 0.83 ± 0.07  | ...          |
| Power-law index                        | 0.83 ± 0.02  | 0.82 ± 0.04  | 0.77 ± 0.05  | 1.14 ± 0.05  |
| Power-law normalization (photons keV^{-1} cm^{-2} s^{-1}) | (1.61 ± 0.32) × 10^{-2} | (1.03 ± 0.26) × 10^{-2} | (1.01 ± 0.27) × 10^{-2} | (3.88 ± 0.07) × 10^{-2} |
| Cutoff energy (keV)                    | 7.89 (fixed) | 7.89 (fixed) | 7.89 (fixed) | 7.89 (fixed) |
| e-folding energy (keV)                 | 27.1 (fixed) | 27.1 (fixed) | 27.1 (fixed) | 27.1 (fixed) |
| Reduced $\chi^2$                      | 2.69 (1259 dof) | 1.23 (1253 dof) | 1.11 (1283 dof) | 1.20 (120 dof) |

**Notes.—** Case 1: Without a blackbody component, for PN, MOS1, and MOS2. Case 2: With a blackbody component, for PN, MOS1, and MOS2. Case 3: Without a blackbody component, for PCA. Case 4: With a blackbody component, for PCA.

For cases 1, 2, and 3 we multiplied the entire model by a factor varying with the instrument to account for the different normalizations. The value of the constant was fixed at 1.00 for EPIC PN.

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(Additional content and analysis related to the table and figure are omitted for brevity.)
6.6 × 10^{-10} \text{ ergs s}^{-1} \text{ cm}^{-2}. Assuming a source distance of 3.2 kpc (Baykal et al. 2002), this value corresponds to a luminosity of 7.5 × 10^{35} \text{ ergs s}^{-1}. To compare with the average X-ray flux, we found the 3–20 keV flux of the January 6 observation to be 6.1 × 10^{-10} \text{ ergs s}^{-1} \text{ cm}^{-2}. This value is approximately 10% greater than the 57.5 day average 3–20 keV RXTE PCA flux. This is reasonable, since the XMM-Newton observation took place 3.55 days after the periastron passage, when the X-ray flux approximately reaches its maximum (see Figs. 5 and 8 of Baykal et al. 2000b). It should be noted that the line parameters obtained from the 3–20 keV RXTE PCA data agree with those obtained from the XMM-Newton EPIC data. However, exclusion of the blackbody component, while fitting RXTE PCA data only, increases the absorption column density and equivalent width of the line emission and makes the power-law index harder, as shown in Table 1, case 4.

To study the spin phase–resolved spectra using EPIC PN data, we divided the spin phase into 10 bins and fitted the 1–10 keV spectrum of each bin with a model including a blackbody component (i.e., the model in case 3). Figure 4 is a plot of the spectral parameters as a function of the spin phase. For all the spin phases, we found that the model gives an iron-line peak energy consistent with 6.42 ± 0.04 keV within 1 \sigma, so we chose to fix this parameter. We also checked the consistency of freezing the cutoff energy, iron-line \sigma, and e-folding energy parameters and found that these parameters did not vary significantly when they were thawed. From Figure 4, the strong modulation (by a factor of \sim 10) of the blackbody flux with spin phase is evident. Similarly, the flux of the power-law component is shown to vary with the spin phase, but the variation is more moderate (by a factor of \sim 3) than that of the blackbody component. The iron-line feature at 6.42 keV is stronger for the off-pulse phases, when the X-ray flux was lower.

4. DISCUSSION AND CONCLUSION

4.1. QPO Feature of SAX J2103.5+4545

QPOs in the X-ray band with periods in the range of \sim 2.5–100 s have been observed in many accretion-powered X-ray pulsars: 4U 0115+63 (Soong & Swank 1989), EXO 2030+375 (Angelini et al. 1989), 4U 1626–67 (Shinoda et al. 1990), SMC X-1 (Angelini et al. 1991), Cen X-3 (Takeshima et al. 1991), V0332+53 (Takeshima et al. 1994), A0535+262 (Finger et al. 1996), GRO J1744–28 (Zhang et al. 1996; Kommers et al. 1997), X Per (Takeshima 1997), 4U 1907+09 (in’t Zand et al. 1998; Mukerjee et al. 2001), XTE J1858+034 (Paul & Rao 1998), LMC X-4, and Her X-1 (Moon & Eikenberry 2001a, 2001b). The QPO feature that we found in the XMM-Newton EPIC PN light curve of SAX J2103.5+4545, which has a peak period of 22.7 ± 0.6 s and fractional rms amplitude of 6.6% ± 1.9%, is quite typical (e.g., In’t Zand et al. 1998; Paul & Rao 1998; Takeshima et al. 1994).

Models that explain the QPO phenomenon in accretion-powered X-ray pulsars fall basically into three categories: In the Keplerian frequency model, QPOs are due to inhomogeneities at the inner edge of the Keplerian disk (\rho_d) that modulate the light curve at the Keplerian frequency, \nu_{\text{QPO}} = \nu_K (\text{van der Klis et al. 1987}). In the beat frequency model, the accretion flow onto the neutron star is modulated at the beat frequency between the Keplerian frequency at the inner edge of the accretion disk and the neutron star spin frequency, \nu_{\text{QPO}} = \nu_K - \nu_s (Alpar & Shaham 1985). The third model involves accretion flow instabilities (Fronter et al. 1989; Lamb 1988) and applies only to the sources that have luminosities close to the Eddington limit; therefore, it should not be applicable to our case, for which the luminosity is well below the Eddington limit.

In our case the QPO frequency \nu_{\text{QPO}} = 4.4 \times 10^{-2} \text{ Hz} is about 1 order of magnitude greater than the spin frequency \nu_s = 2.8185 \times 10^{-3} \text{ Hz}. Therefore, it is difficult to distinguish between a Keplerian model and a beat frequency model.
Assuming that the 22.7 s oscillation in SAX J2103.5+4545 is related to the Keplerian orbital motion via either the Keplerian frequency model or the beat frequency model, and using the QPO and its FWHM values, we obtain the radius of inner disk as

$$r_0 = \left(\frac{GM}{4\pi^2}\right)^{1/3} \frac{k^{-2/3}}{\mu} = \left(1.32 \pm 0.13 \times 10^{-3}\right) \times 10^9 \text{ cm},$$

(2)

where $M$ is 1.4 $M_\odot$ for a neutron star and $G$ is the gravitational constant.

From the strong correlation between pulse frequency derivatives and X-ray flux, Baykal et al. (2002) obtained for the distance to the source 3.2 ± 0.8 kpc, and for the magnetic field (12 ± 3) × 10^{12} G. Using the distance and magnetic field values, the inner edge of the Keplerian disk $r_0$ can be found as (Ghosh & Lamb 1979)

$$r_0 \simeq 0.52 \mu^{4/7} (2GM)^{-1/7} M^{-2/7} = \left(1.67^{+0.22}_{-0.33}\right) \times 10^9 \text{ cm},$$

(3)

where $\mu = BR^3$ is the neutron star magnetic moment, with $B$ the equatorial magnetic field, $R$ the neutron star radius, and $M$ the mass accretion rate, with a value of $\frac{GM}{4\pi^2} r_0^{2/3} = \left(3.32 \pm 0.13 \times 10^{-3}\right) \times 10^9 \text{ cm},$ for the case of inner disk radius.

The radius of the inner disk inferred from the Keplerian orbital motion of inhomogeneities and the one inferred from the Ghosh-Lamb disk accretion model agree with each other. This shows that the idea that the QPOs are formed as a result of the Keplerian motion of inhomogeneities is indeed promising, as the explanation of the QPO of SAX J2103.5+4545 and the observed QPO frequency is consistent with the distance and the magnetic field values estimated by Baykal et al. (2002).

4.2. Blackbody and Iron-Line Features of the Energy Spectrum

XMM-Newton observations of SAX J2103.5+4545 revealed for the first time that the energy spectrum of the source has a blackbody component peaking at ~1.90 keV, with an emission radius of ~0.3 km. The blackbody radiation may come from the blackbody component is relatively more significant for the relatively small blackbody emission radius (~0.3 km) compared to these X-ray pulsars. Although the contribution of the blackbody component is relatively more significant for lower energies (i.e., energies smaller than ~3 keV), the power-law flux is ~3 times greater than the blackbody flux even at the 1–3 keV energy band.

In our case, it is unlikely that the blackbody emission comes from the reprocessed emission of the surrounding material or the accretion disk, as in the case of Her X-1 (Endo et al. 2000), Cen X-3 (Burderi et al. 2000), SMC X-1, and LMC X-4 (Paul et al. 2002), since the blackbody component in such cases is expected to be softer ($kT \sim 0.1$ keV). The lower blackbody temperature and smaller blackbody emission radius at the off-phase shown in Figure 4 are also indications of the plausibility of the polar cap emission interpretation, as the regions of the soft polar cap emission must align with the peak of the X-ray pulse of the pulsar.

Using spin-phase–resolved spectroscopy, the strength of the iron-line feature at ~6.42 keV was also found to vary significantly with the spin phase, as seen in Figure 4. The peak energy of this feature clearly shows that it corresponds to the fluorescent iron K-line complex. This line complex feature is observed in the spectra of most X-ray pulsars (White et al. 1983; Nagase 1989) and is generally thought to be produced by ions of lower valence than Fe xviii in the relatively cool matter around the neutron star (e.g., accretion disk or accretion disk corona) by fluorescent Kα transition.

Variation of the iron-line feature with the spin phase can then be interpreted as a sign that it is mainly produced outside the polar cap region of the neutron star and thus should have a peak at the off-pulse parts of the spin phase. From Figure 4 we see that the iron-line flux and iron-line equivalent width vary strongly with the spin phase, peaking at the off-pulse. Similar pulse-phase dependence of the iron-line feature is also observed in Her X-1 (Choi et al. 1994).

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