PASJ: Publ. Astron. Soc. Japan **56**, 175–179, 2004 February 25

Discovery of a Peculiar Pulsar in the Small Magellanic Cloud

Masaru UENO,[1] Hiroya YAMAGUCHI,[1] Shin-ichiro TAKAGI,[1] Jun YOKOGAWA,[2] and Katsuji KOYAMA[1]
[1]*Department of Physics, Graduate School of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502*
[2]*Comtas Group Co., Ltd., AXA Kure-building 3F, Chuo 1-6-9, Kure, Hiroshima 737-0051*
masaru@cr.scphys.kyoto-u.ac.jp, hiroya@cr.scphys.kyoto-u.ac.jp, takagi9@cr.scphys.kyoto-u.ac.jp,
yokogawa@comtas.jp, koyama@cr.scphys.kyoto-u.ac.jp

(Received 2003 November 5; accepted 2003 December 12)

Abstract

We report on a peculiar X-ray binary pulsar, IKT 1 = RX J0047.3−7312, observed with XMM-Newton in 2000 October. The X-ray spectrum is described by a two-component spectrum. The hard component has a broken power-law with respective photon indices of 0.2 and 1.8, below and above the break energy at 5.8 keV. The soft component can be modeled by a blackbody of $kT = 0.6$ keV. The X-ray flux shows a gradual decrease and periodic variations of about 4000 s. The averaged flux in 0.7–10.0 keV is $2.9 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, which is $\sim$ 10-times brighter than that in a ROSAT observation in 1999 November. In addition to the 4000-s variation, we found coherent pulsations of 263 ± 1 s. These discoveries strengthen the Be/X-ray binary scenario proposed by the ROSAT and ASCA observations on this source, and confirm that most of the hard sources in the Small Magellanic Cloud are X-ray binary pulsars. A peculiar property of this XBP is that the coherent pulsations are found only in the soft component, and the folded light curve shows a flat top shape with a sharp dip. We discuss the nature of this XBP focusing on the peculiar soft component.

Key words: stars: neutron — stars: pulsars: individual (IKT 1) — X-rays: individual (IKT 1) — X-rays: stars

1. Introduction

More than 30 X-ray binary pulsars (XBP) have been discovered in the Small Magellanic Cloud (SMC) by recent satellites, such as ASCA, RXTE, Chandra, and XMM-Newton (e.g., Yokogawa et al. 2003). Most of the XBPs in the SMC have been classified, or proposed to be Be/X-ray binaries with estimated ages of $\sim 10^7$ yr. The number of XBPs normalized to the galaxy mass is far larger in the SMC than in our Galaxy (Haberl, Sasaki 2000; Yokogawa et al. 2003). This high population of XBPs would be good evidence for active star formation in the SMC $\sim 10^7$ yr ago.

Other than the population study of X-ray sources, the SMC is a good local galaxy for studying individual X-ray sources, such as the emission mechanism of XBPs, because the interstellar extinction for the member sources is very low and the line-of-sight galaxy depth is small ($\sim$ 10 kpc) compared to the SMC distance of $\sim$ 60 kpc (Harries et al. 2003 and references therein). The former gives us soft X-ray information down to a few-hundred eV, while the latter provides a more accurate distance, and hence the X-ray luminosity, than those of the galactic sources. The large collective area of XMM-Newton enables us to perform X-ray spectroscopy down to luminosities of $\sim 10^{34}\,\mathrm{erg\,s^{-1}}$ (e.g., Sasaki et al. 2003), even for more distant (60 kpc) XBPs than those in our Galaxy (typically 1–20 kpc).

IKT 1 was first discovered by Inoue, Koyama, and Tanaka (1983) with Einstein Observatory. ROSAT observed this source many times and Haberl and Sasaki (2000) proposed this source to be a Be/X-ray binary candidate from the flux variability and the existence of an optical counterpart with emission lines. ASCA also detected this source and found a flare-like behavior (Yokogawa et al. 2003). Yokogawa et al. (2003) plotted hardness ratios of X-ray sources in the SMC against their luminosities, and found that XBPs reside in a restricted region. Since IKT 1 is located in this region, IKT 1 is likely to be an XBP.

Using the XMM-Newton archival data, we found coherent X-ray pulsations from this source. This paper reports on the discovery of a 263-s pulsation and the timing and spectrum analysis. A discussion on the nature of IKT 1 is given focusing on phase-resolved spectroscopy. Independent detection of the 263-s pulsation was recently reported by Haberl and Pietsch (2004). The source distance is assumed to be 60 kpc, the same value as the SMC (Harries et al. 2003).

2. Observation

The main objective of the XMM-Newton (Aschenbach et al. 2000) observation made on 2000 October 15 was to study a supernova remnant (SNR), IKT 5 (Inoue et al. 1983), and other X-ray sources around this SNR. In this field, we found IKT 1 with a higher X-ray flux than the previous observations of ROSAT and ASCA, and hence we consider the X-ray properties of this source. Since EPIC/PN (Strüder et al. 2001) has a better time resolution and statistics than MOS1/2 (Turner et al. 2001), and IKT 1 accidentally fell in the CCD dip of MOS2, we concentrate on the X-ray data from EPIC/PN, and use the MOS1 and 2 data for a consistency check.

PN was operated in the extended full-frame mode with the medium filter and a time resolution of 200 ms. We used version 5.4.1 of the Standard Analysis System (SAS) software for event selection. From the detected PN events, we selected those with PATTERN keywords between 0 and 4 as X-ray events. The exposure time was $\sim$ 22 ks.

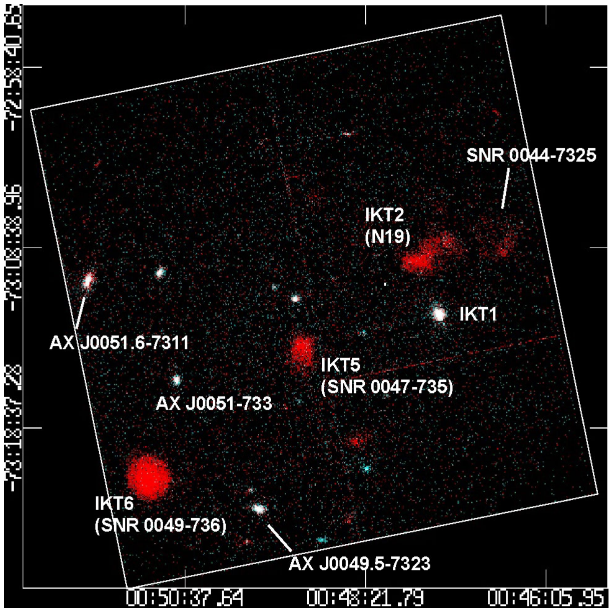

Fig. 1. XMM-Newton/PN image around IKT 5. The soft (0.5–2.0 keV) and hard (2.0–7.0 keV) band images are represented with red and blue colors, respectively. The images have been smoothed to a resolution of 5″. XBPs and SNRs in the FOV are designated with their names. The FOV of the PN detector is indicated by the solid square.

3. Results

3.1. Image Analysis

The hard (2.0–7.0 keV) and soft (0.5–2.0 keV) band X-ray images are shown with two colors in figure 1. Three XBPs (AX J0049.5−7323, AX J0051−733, AX J0051.6−7311; Yokogawa et al. 2000a; Imanishi et al. 1999; Yokogawa et al. 2000c) and 4 SNRs (0044−7325, IKT 2 = N 19, IKT 5 = 0047−735, IKT 6 = 0049−736; e.g., Wang, Wu 1992) are clearly found in the field of view (FOV). All of the XBPs appear as white point sources, and the SNRs show red extended structures. Blue color sources may be AGNs. All the three pulsars mentioned above are identified with emission line objects (ELOs) cataloged by Meyssonnier and Azzopardi (1993) (Haberl, Sasaki 2000). The coordinates of these pulsars derived from the PN data are systematically shifted from the positions of the optical counterparts by (ΔRA, ΔDec) = ($-2.''4$, $-0.''1$). We hence fine-tuned the PN coordinates to the optical coordinates. After this tuning, the root-mean-square of the differences between the PN and the optical positions for the three pulsars is (ΔRA, ΔDec) = ($0.''2$, $0.''7$). This can be used as a typical positional error between the two frames.

The brightest source in the FOV is a white point source south of IKT 2. The fine-tuned position is RA = $00^{\rm h}47^{\rm d}23.^{\rm s}3$, Dec = $-73^\circ 12' 27''$ (J2000), and hence we designate this source as XMMU J004723.3−731227. Although the $1\,\sigma$-statistical error of this source position is only $0.''1$, the realistic error would be $\sim 0.''7$ (see the previous paragraph). Since all of the error regions of XMMU J004723.3−731227, IKT 1 (Inoue et al. 1983), and RX J0047.3−7312 (Haberl, Sasaki 2000) overlap, we conclude that these three sources are the same X-ray object.

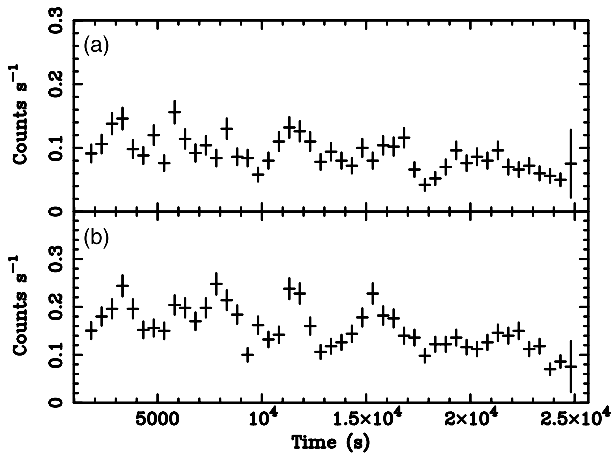

Fig. 2. Light curves of IKT 1 in the 0.5–2.0 (a), and 2.0–10.0 keV (b) bands.

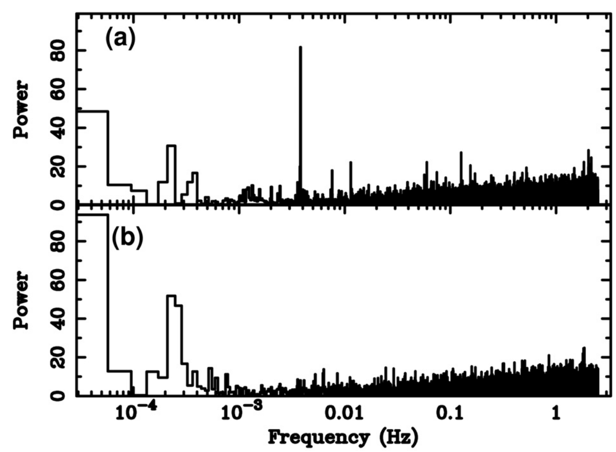

Fig. 3. Power spectra of IKT 1 in the 0.5–2.0 (a) and 2.0–10.0 keV (b) bands. The power is normalized to be 2 for random fluctuations. The peak at $\sim 3.82 \times 10^{-3}$ Hz is seen only in the 0.5–2.0 keV band.

3.2. Timing Analysis

For a timing analysis of IKT 1, X-ray photons were extracted from a circular region of 40″ radius centered on IKT 1 in the PN image. Light curves with a time bin of 500 s in the energy bands of 0.5–2.0 and 2.0–10.0 keV are shown in figure 2. In both energy bands, we can see several flare-like events on the general trend of decreasing flux.

After barycentric arrival-time corrections, we searched for periodicity in the energy bands of 0.5–2.0 and 2.0–10.0 keV, using a Fast Fourier Transformation algorism. Figure 3 shows the resultant power density spectra in the 3.8×10^{-5}–2.5 Hz frequency band. In the 0.5–2.0 keV band, a maximum power of 81.6 was obtained at a frequency of 3.82×10^{-3} Hz (= 262 s). Since the probability to detect such a large power at any frequency from random events is only $\sim 1 \times 10^{-13}$, the detection of coherent pulsations is highly significant. In the 2.0–10 keV band, however, we see no significant power excess

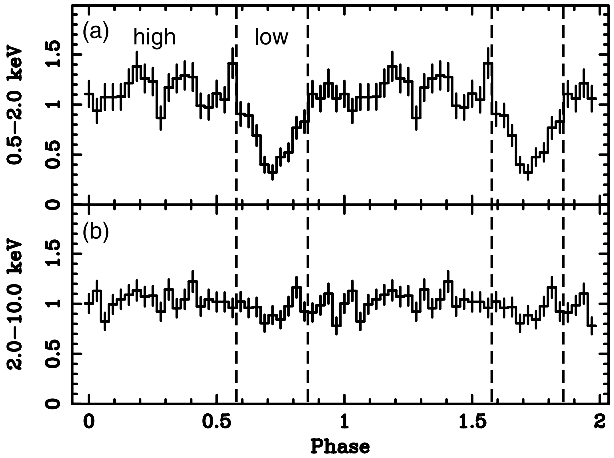

Fig. 4. Pulse profiles folded with the best pulse period of 263 s in the two energy bands: 0.5–2.0 keV (a), and 2.0–10.0 keV (b). The phase-averaged count rates are normalized to be unity.

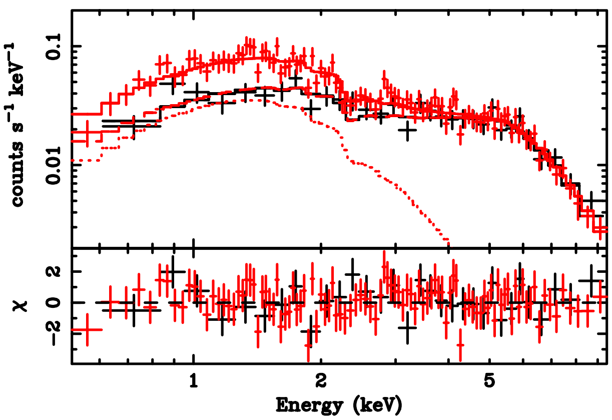

Fig. 5. (Upper panel) Background-subtracted spectra in the "low" (black) and "high" (red) phases. The best-fit models and the blackbody component are indicated by the solid and dotted lines, respectively. (Bottom panel) Residuals of the source counts from the best-fit models.

at this frequency. The other large power peak at 2.29×10^{-4} Hz is due to periodic flares. Unlike coherent pulsations, this peak is found in both energy bands.

We next performed epoch folding searches for the periods near to the two power-peak frequencies. The flare-like events are found to have the most probable period of 3920 ± 150 s. The barycentric period of the coherent pulsations is determined to be $P = 263 \pm 1$ s. Figure 4 shows the folded pulse profiles at the best period of 263 s in the 0.5–2.0 and 2.0–10.0 keV bands. We see no pulse modulation in the hard X-ray band, while the pulse profile found in the soft band is very peculiar: a flat-top profile with a V-shape dip.

3.3. *Spectral Analysis*

The X-ray spectrum was extracted from the same region as the timing analysis (the 40″-radius circle), while the background spectrum was extracted from the annular region around the source with inner and outer radii of 40″ and 80″, respectively.

Table 1. Best-fit parameters with a broken power-law plus blackbody model.

Parameters	Value[§]
Broken power-law	
Γ_1*	$0.19^{+0.09}_{-0.30}$
Γ_2*	$1.8^{+0.6}_{-0.4}$
Break energy [keV]	$5.5^{+0.4}_{-0.6}$
Norm[†]	$6.7^{+1.0}_{-2.0}$
Blackbody	
kT [keV]	$0.59^{+0.11}_{-0.10}$
$L_{\rm total}$ ("low")[‡]	< 0.5
$L_{\rm total}$ ("high")[‡]	$1.4^{+0.6}_{-0.3}$
$N_{\rm H}$ [cm^{-2}]	$(9.6^{+4.6}_{-4.4}) \times 10^{20}$

* Photon indices below (Γ_1) and above (Γ_2) the break energy.
† Normalization at 1 keV ($\times 10^{-5}$ photons keV^{-1} cm^{-2} s^{-1}).
‡ Total luminosity ($\times 10^{35}$ erg s^{-1}) of the blackbody component in the "low" and "high" phases at the SMC distance (60 kpc; Harries et al. 2003).
§ Error regions correspond to 90% confidence levels.

Since the pulse profiles are energy dependent, we made X-ray spectra separately during the pulse minimum (low) and maximum (high) phases as shown in figure 4. The background-subtracted spectra for the low and high phases are given in figure 5. In the hard X-ray band above ~ 3 keV, the two X-ray spectra show essentially the same profile and flux, while below ~ 2 keV the spectrum of the high phase shows a large excess over that of the low phase. This is in excellent agreement with that the X-ray pulsation is found only in the soft X-ray band.

Since both spectra have a break at ~ 6 keV, we fitted the spectra with a broken power-law model. The photon indices, break energies and normalizations were simultaneously fitted, while the absorption columns were treated independently for each spectrum. In the present work, the photoelectric absorption was calculated using cross sections by Morrison and McCammon (1983), assuming the solar abundance ratio (Anders, Grevesse 1998). This model reproduced the hard energy band well, but left large residuals at the soft energy band, and was statistically rejected with a χ^2/degree of freedom (d.o.f.) = 160.9/129. Therefore, the X-ray pulsation is not due to a periodic variation of the absorption.

We then added a blackbody (BB) as the soft component to the broken power-law model and performed a simultaneous fit for the low- and high-phase spectra. The normalizations of the BB component were treated as independent parameters between the two phases. As a result, the fit was acceptable with a χ^2/d.o.f. = 125.9/127, with the best-fit parameters and models given in table 1 and figure 5, respectively.

As for the 4000-s periodicity, we also made separate spectra for the high and low-flux phases using the 4000-s folded light curve. These spectra were simultaneously fitted with the same two-component model as that for the case of coherent pulsation (263 s); we fixed the spectral parameters to the best-fit values given in table 1, except for the normalizations. In this

Table 2. Flux history of IKT 1.*

Satellite/Detector	MJD	Count rate†	Flux‡
Einstein/IPC	44189	3.9 ± 0.8	5.2 ± 1.1
ROSAT/PSPC	48538	$0 \quad \pm 3$	$0 \quad \pm 5$
/PSPC	48728	11.0 ± 0.8	$17 \quad \pm 1$
/HRI	49098	1.3 ± 0.6	$5 \quad \pm 2$
/PSPC	49297	2.0 ± 0.6	2.9 ± 0.8
/HRI	49460	0.9 ± 1.0	$4 \quad \pm 4$
/HRI	49462	1.2 ± 1.4	$5 \quad \pm 6$
/HRI	49639	-0.4 ± 1.3	$-2 \quad \pm 5$
ASCA/GIS§	50765	···	6.7
/GIS§	51646	···	14
XMM/PN	51832	234 ± 3	29

* Uncertainties correspond to 1-σ confidence regions.
† Count rate ($\times 10^{-3}$ cnts s^{-1}).
‡ X-ray flux ($\times 10^{-13}$ erg cm^{-2} s^{-1}) in the 0.7–10.0 keV band.
§ Cited from Yokogawa et al. (2003).

case, we found an acceptable fit when the BB component was constant, but only the normalizations of the broken power-law component varied between the high and low phases. Therefore, the 4000-s variation is attributable to the broken power-law component.

4. Long-Term Flux History

To investigate a long-term flux variability, we accessed the HEASARC archive, and found that IKT 1 was in the field of 1 Einstein/IPC, 6 ROSAT/PSPC, and 4 ROSAT/HRI observations. We extracted the source events from circular regions of 60″, 50″, and 20″ radii centered on IKT 1 for the Einstein/IPC, ROSAT/PSPC, and HRI observations, respectively. The backgrounds were estimated using the same size regions in blank skies near to the source. After background subtraction and a vignetting correction, we estimated the source fluxes using the PIMMS software, and using the ASCA best-fit model (Yokogawa et al. 2003). For a comparison, the phase-averaged flux of the XMM-Newton observation was also estimated using the same ASCA model. In table 2, we summarize the long-term X-ray fluxes (0.7–10.0 keV). We can see that the XMM-Newton flux at MJD 51832 is higher than the Einstein, ROSAT, and ASCA fluxes by more than ~ 5 times. Thus, a large long-term flux variation is clearly found. It should be noted that, in the ASCA observation, IKT 1 exhibited a large flare of about 10^4 s duration (Yokogawa et al. 2003).

5. Discussion

5.1. *X-Ray Population*

The large long-term variability and the relatively low luminosity ($\sim 10^{35\text{–}36}$ erg s^{-1} from the ROSAT to XMM-Newton observations) suggest that IKT 1 is a wind-fed binary system. Meyssonnier and Azzopardi (1993) detected an emission-line star from a star cluster near IKT 1. Using the ROSAT observation, Haberl and Sasaki (2000) proposed that one of the stars in this cluster is an optical counterpart of IKT 1. We found that only one cluster member in the OGLE-II star catalog (Zebrun et al. 2001), OGLE 004723.37−731226.9, is within the refined position error of IKT 1 by the EPIC/PN observation (the radius of $\sim 0.''7$), and hence this star must be an optical counterpart of IKT 1. The long-term X-ray variation, the pulsation of 263 s and the power-law spectrum strongly support that IKT 1 is a Be/X-ray binary pulsar (Be/XBP).

Since the space density of XBPs is extremely high in the south-west part of the SMC (see figure 1), and most of the XBPs are Be/XBPs or strong candidates (Imanishi et al. 1999; Yokogawa et al. 2000a, 2000c), this region must be an active star-formation site of some $\sim 10^7$ yr ago. A H I supergiant shell runs over this area (Stanimirović et al. 1999) and the age of the shell is estimated to be about 10^7 yr. This supergiant shell, therefore, probably triggered the proposed star-formation activity about 10^7 years ago.

5.2. *Origin of the Soft Component*

Although our results put IKT 1 to be a strong candidate of Be/XBPs, the detailed X-ray features, the presence of a pulsating soft component and the absence of pulsation in the power-law component, are rather peculiar compared to the other Be/XBPs. The pulse profile of a flat top with a V-shape dip is also unique.

Among the about 30 XBPs (and candidates) in the Magellanic Clouds, the soft component has been observed from only a few sources: SMC X-1 (Marshall et al. 1983; Woo et al. 1995), LMC X-4 (Woo et al. 1996), RX J0059.2−7138 (Kohno et al. 2000), EXO 05319−6609.2 (Haberl et al. 2003), and XTE J0111.2−7317 (Yokogawa et al. 2000b) (see also Paul et al. 2002, and references therein), in which the latter 3 are Be/XBPs. Thus, IKT 1 may be the fourth Be/XBP with a clear soft component.

For RX J0059.2−7138, the soft component is modeled as a thin thermal plasma of $kT = 0.37$ keV and exhibits no pulsation (Kohno et al. 2000). Thus, the origin would be a largely extended plasma of a comparable size with the binary separation. EXO 053109−6609.2, on the other hand, shows a pulsation above 0.4 keV, and both the soft and hard components may be pulsed (Haberl et al. 2003). Thus, the origin of the soft component must be comparable to or smaller than the size of a neutron star (NS). XTE J0111.2−7317 has a peculiar spectrum of an inversely broken power-law model, and shows pulsations both below and above the break energy (Yokogawa et al. 2000b). Unlike these 3 sources, IKT 1 shows X-ray pulsations only in the soft component.

Sasaki, Pietsch, and Haberl (2003) reported that two XBPs in the SMC show pulsations mainly in the soft band. AX J0049.5−7323 (Yokogawa et al. 2000a) and RX J0101.3−7211 (Sasaki et al. 2001) also show pulsations mainly in the soft components. The statistics of all the sources, however, were limited to distinguish whether or not the X-ray spectra are composed of pulsed soft and non-pulsed hard components. Accordingly, IKT 1 is the first object that exhibits a two-component spectrum with a pulsed soft component and a non-pulsed hard component. The soft component can be modeled with BB radiation of 0.59 keV temperature. Using the X-ray luminosity of this BB in the high phase of the pulsation, the emission size is estimated to be 1.2×10^2 km^2. This size is about 10% of the full surface of NS, and hence flux modulation along the NS rotation would be expected. A possible origin of the soft X-rays might be an opaque shell at the magnetosphere, which was first proposed by McCray and Lamb (1976) for the pulsating soft emission from Her X-1. Although the luminosity, and hence the emission size of the soft emission from IKT 1 are significantly smaller than Her X-1, this model is another possible origin of the pulsating soft X-ray emission.

5.3. *Origin of the Hard Component*

In general, XBPs exhibit a broken power-law spectrum in the hard component, which is likely to come from the small region near to the pole, possibly the accretion column. The abnormal Thomson scattering in the strong magnetic field and the cyclotron resonance absorption/emission would be responsible for the spectral break. Since the hard component of IKT 1 has a typical broken power-law spectrum, it is highly possible that these X-rays originate from the accretion column near to the magnetic pole. A big puzzle, however, is that no coherent pulsation is found from this power-law component.

Except for pulsations, the power-law component is highly variable with many flares with about 4000-s quasi-periodicity. A plausible case is that the 4000-s variation is due to quasi-periodic mass accretion. In fact, a long exposure (177 ks) observation of ASCA (Yokogawa et al. 2003) showed a large flare with a duration of about 10^4 s. No hint of the 4000-s variations was, however, found in the flare. The fainter flux of IKT 1 and the smaller effective area of ASCA than that of XMM-Newton might have made it impossible to detect the 4000-s variations, if any.

Quasi-periodic oscillations (QPOs) at frequencies of 5–220 mHz have been observed from ~ 10 XBPs to date (e.g., Boroson et al. 2000, and references therein). The canonical model of QPOs in XBPs is either a model of the beat-frequency between those of rotations of the NS ($\nu_{\rm ns}$) and the Kepler motion of the inner disk ($\nu_{\rm K}$) (a beat frequency model: BFM), or a Keplerian frequency model (KFM). In the BFM, the QPO frequency ($\nu_{\rm QPO}$) equals ($\nu_{\rm K} - \nu_{\rm ns}$), where in the IKT 1 case $\nu_{\rm QPO} = 0.23$ mHz and $\nu_{\rm ns} = 3.82$ mHz. As a result, $\nu_{\rm K}$ of IKT 1 must be about 4 mHz and the corresponding Keplerian radius is about 7×10^9 cm. The disk matter at the inner Keplerian radius should be in pressure balance with the magnetospheric field. Then, assuming the radius and mass of NS to be $R_0 = 15$ km, $m_{\rm x} = 1.4\,M_\odot$, and using the X-ray luminosity of $L_{\rm x} = 1.3 \times 10^{36}$ erg s^{-1}, we estimate the surface magnetic field strength of the NS to be $\sim 4 \times 10^{13}$ G (cf. Davidson, Ostriker 1973). This value is beyond the range of normal NSs (or XBPs), and hence the BFM is unlikely. In the KFM, the Keplerian orbital period (frequency) of the inner disc is $\nu_{\rm K} = \nu_{\rm QPO} = 0.2$ mHz, and hence the radius is about 5×10^{10} cm, which is too far from the NS to produce the hard X-rays that we observed.

In summary, IKT 1 exhibits many unusual properties as an XBP, which must be a key for understanding the nature and X-ray emission mechanisms of this source. For a more quantitative study of this peculiar pulsar, a very long-exposure observation with high-sensitivity instruments, like XMM-Newton, is highly anticipated.

The Einstein and ROSAT data were obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. M.U. and S.T. are supported by JSPS Research Fellowship for Young Scientists. This work is supported by a Grant-in-Aid for the 21 century COE, “Center for Diversity and Universality in Physics”.

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