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Observations of the Peculiar Hard X-Ray Transient X0331+53 (V0332+53)

Kazuo MAKISHIMA and Takaya OHASHI

Department of Physics, Faculty of Science, The University of Tokyo,
3-1, Hongo 7-chome, Bunkyo-ku, Tokyo 113

Nobuyuki KAWAI and Masaru MATSUOKA

Cosmic Ray Laboratory, The Institute of Physical and
Chemical Research, 2-1 Hirosawa, Wako, Saitama 351-01

Katsuji KOYAMA, Hideyo KUNIEDA, Yuzuru TAWARA, and Naoko USHIMARU

Department of Astrophysics, School of Science, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya 464-01

Robin H. D. CORBET, Hajime INOUE, Tsuneo KII,
Fumiyoshi MAKINO, Kazuhisa MITSUDA,
Toshio MURAKAMI, Fumiaki NAGASE, Yoshiaki OGAWARA, and Yasuo TANAKA

Institute of Space and Astronautical Science,
1-1, Yoshinodai 3-chome, Sagamihara, Kanagawa 229

and

Shunji KITAMOTO, Shigenori MIYAMOTO, Hiroshi TSUNEMI,
and Koujun YAMASHITA

Department of Physics, Faculty of Science, Osaka University,
1-1, Machikaneyama, Toyonaka, Osaka 560

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Abstract

Tenma observations were made of the transient 4.4-s X-ray pulsar X0331+53 (V0332+53) at several phases of its 34-d binary orbit during the period November 1983 – January 1984. The measured X-ray flux and pulse periods agree with those obtained with EXOSAT. Rapid random fluctuations in the X-ray emission from this source were studied. It appears that this type of variability is not rare among accreting pulsars, but is particularly noticeable in X0331+53 due to the small pulse fraction. The X-ray spectra show a turn-over above ~15 keV, which is better described by a recently introduced cyclotron absorption formula than the commonly used exponential cutoff model. This also applies to the spectra of Her X-1 and Cen X-3. In terms of this model, a magnetic field strength of $\sim 3 \times 10^{12}$ G is suggested for X0331+53. The absence of iron K-emission lines in the spectra indicates a rather small circumstellar matter density. This, together with the observed high luminosity ($\sim 3 \times 10^{36}$ erg s^{-1}) and large intensity modulation along the orbit, suggests that the pulsar is powered by accretion from the equatorial envelope of the supposedly Be-type primary (BQ Cam).

Key words: Be stars; X-ray binaries; X-ray pulsars; X-ray sources.

1. Introduction

We report here on observations of a peculiar hard X-ray transient, X0331+53 (= V0332+53), made with the X-ray satellite Tenma. The source had been detected in 1973 with Vela 5B in a bright (~1 Crab) outburst, and had been designated V0332+53 (*IAU Circular*, No. 3893, 1983; Terrell and Priedhorsky 1984). Re-discovered ten years later by Tenma in 1983 November (*IAU Circular*, No. 3891, 1983), it was then observed with Tenma and EXOSAT (Stella et al. 1985, hereafter S85), as well as in the optical and infrared. X0331+53 has been established as being a 4.4-s pulsator (*IAU Circular*, No. 3902, 1983) in a 34-d binary (*IAU Circular*, No. 3912, 1984; S85). It has been identified optically with the 15 mag star BQ Cam. With strong Hα emission and infrared excess in correlation with X-ray outbursts (Bernacca et al. 1984; Kodaira et al. 1985; Iye and Kodaira 1985; Corbet et al. 1986, hereafter called CCV86; Coe et al. 1987), the optical counterpart is likely to be a reddened Be star (Kodaira et al. 1985; Stocke et al. 1985; Iye and Kodaira 1985; CCV86).

The X-ray behavior of X0331+53 is rather peculiar compared with ordinary binary X-ray pulsars, which are believed to involve magnetized neutron stars. First of all, shallow 4.4-s pulsations are dominated by random rapid X-ray fluctuations (*IAU Circular*, No. 3891, 1983), which had previously been found only in a few X-ray binaries (Cyg X-1, GX 339−4 etc.) that are thought to be black-hole systems. In contrast, X0331+53 varied little on medium time scales (~hours), unlike ordinary wind-fed pulsars. The iron K-emission line, often seen in the spectra of X-ray pulsars (Nagase 1989), was not detected from X0331+53. The properties of this object thus encourage further study of X-ray emission mechanisms from magnetized neutron stars, especially in comparison with those of the Galactic black hole candidates.

2. Observations

The observations were carried out with the gas scintillation proportional counters (GSPC) (Koyama et al. 1984) on board Tenma (Tanaka et al. 1984). During an attitude maneuver made on 1983 November 14, an X-ray nova of ~70 mCrab intensity was discovered in a sky region near $\alpha = 3^{\rm h}30^{\rm m}$ and $\delta = 53^\circ$. The nova had a very hard spectrum and exhibited rapid random X-ray variability on time scales down to 0.5 s (*IAU Circular*, No. 3891, 1983). Based on the source location determined with the star aspect sensor and the rotation modulation collimator, we designated the source to be X0331+53. Using a limited amount of quick-look data, we searched for pulsations, without success. The announcement of these discoveries led to a position improvement by EXOSAT (*IAU Circular*, No. 3893, 1983), and then to an optical identification with BQ Cam, at $\alpha = 3^h31^m14^s.85$ and $\delta = 53°00'24''.5$ (1950.0; *(IAU Circular*, No. 3893 and No. 3897, 1983). Meanwhile, EXOSAT discovered weak but coherent 4.4-s pulsations in the X-ray flux (*IAU Circular*, No. 3902, 1983), which we confirmed based on a longer data base. We also became aware of the previous outburst detected by Vela 5B (*IAU Circular*, No. 3893, 1983).

Figure 1a shows the X-ray lightcurve of X0331+53, obtained in pointed observations which started on November 15. It covers the outburst roughly from its rise to its end. From this and the observed spectra, the 2–30 keV X-ray flux F_x and luminosity L_x at the flare peak are estimated to be :

$$F_x = 3.2 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \tag{1}$$

and

$$L_x = 3.4 \times 10^{36} \, (d/3\text{kpc})^2 \text{ erg s}^{-1}, \tag{2}$$

in agreement with S85. Here, d is the source distance, and the optical estimate of d = 2–4 kpc (Stocke et al. 1985; CCV86) implies that $L_x = (1.5\text{–}6) \times 10^{36}$ erg s^{-1}. This is comparable to those of similar systems, e.g., 4U 0115+63 [$\sim 10^{37}$ erg s^{-1}; Rose et al. (1979) and Kriss et al. (1983)] and A0535+26 [$\sim 8 \times 10^{36}$ erg s^{-1} as average peak luminosity; Janot-Pacheco et al. (1987)].

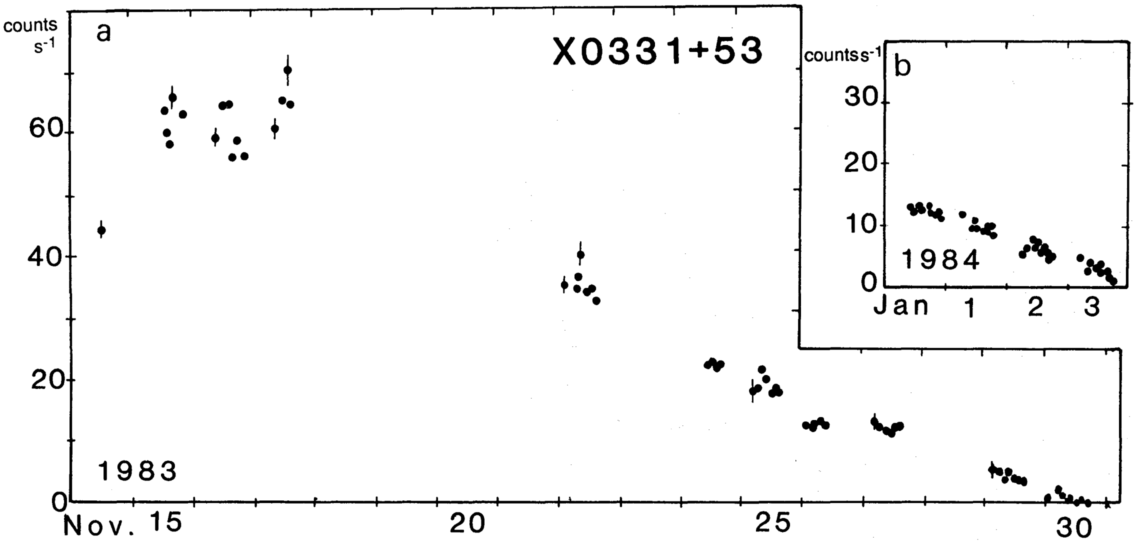

Fig. 1. The 3–20 keV X-ray lightcurve of the two outbursts from X0331+53. The count rates are for an effective area of 640 cm^2 of the GSPC.

In late 1983 December, a second outburst from X0331+53 was detected with EXOSAT (*IAU Circular*, No. 3906, 1984). We, accordingly, resumed the Tenma observations from December 30, and continued them until 1984 January 5. The X-ray light curve from these observations is shown in figure 1b. This reappearance of X0331+53 was suggestive of a one-month periodicity in the source, which was confirmed by the detection of a third outburst by EXOSAT in 1984 January. The subsequent pulse-timing analysis using EXOSAT data (*IAU Circular*, No. 3912, 1984; S85) indeed gave an orbital period of 34.25±0.10 d.

During these Tenma observations, the 2–36 keV GSPC data were acquired either in 128 pulse-height channels (time resolution: 0.5 s or 2.0 s), or in 32 pulse-height channels with a 0.125-s time resolution. The 128-channel data were used for a spectral study, taking advantage of the large effective area (640 cm^2) and good energy resolution (9.5% FWHM at 5.9 keV) of the GSPC. The 32-channel data were mainly used to study the temporal behavior of the source.

3. Results of Spectral Analysis

3.1. Observed Spectra

For the spectral analysis we used data from one GSPC subset (SPC-A, with an effective area of 320 cm^2) only, because one detector from the other subset (SPC-B) had started degrading. Several raw spectra are shown in figure 2. With a flat slope below 10 keV and a steep fall above 15 keV, they resemble those of other X-ray pulsars (White et al. 1983; Nagase 1989). The spectral slope at <10 keV became steeper as the source became fainter. We fitted these spectra with the conventional power-law times exponential cutoff model, i.e., a photon spectrum of the form (Pravdo et al. 1978; White et al. 1983),

$$f(E) = A\,E^{-\alpha}\exp[\,-N_{\mathrm{H}}\,\sigma\,(E)\;-\;H(E)\,]. \tag{3}$$

Here, E is the photon energy, A and α are the normalization and the power-law photon index, respectively, N_{H} is the absorption column, $\sigma(E)$ is the photoelectric absorption cross section by Brown and Gould (1970), and the function

$$H(E) = \begin{cases} 0 & (\,E\;<\;E_{\mathrm{C}}\,) \\ (E - E_{\mathrm{C}})\;/\;E_{\mathrm{F}} & (\,E\;>\;E_{\mathrm{C}}\,) \end{cases} \tag{4}$$

simulates the high-energy cutoff.

As presented in figure 3a and table 1, the best-fit model parameters from these fits agree with the EXOSAT results (S85), and are typical for an X-ray pulsar (White et al. 1983). However, the fit residuals show a systematic discrepancy which makes the fits unacceptable. This discrepancy arises from the abruptness of the break at $E = E_{\mathrm{C}}$ in the model, and from the complex curvature of the observed spectrum at $E > E_{\mathrm{C}}$, which cannot be simulated by an exponential. Equation (4) caused similar discrepancies for the spectra of Her X-1 and Cen X-3 as well (figures 3b, c; table 1). Thus, the failure of this model is not specific to X0331+53 but, rather, common to X-ray pulsars. We further note that the present model is purely an empirical one with little physical meaning.

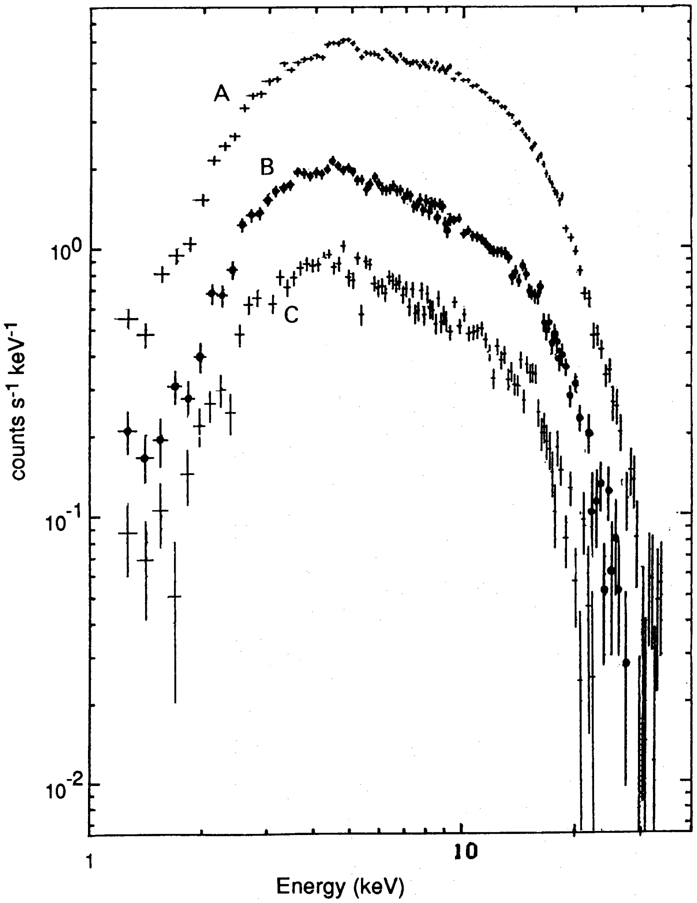

Fig. 2. Raw X-ray spectra of X0331+53 accumulated on 1983 November 16.6–17.8 (labeled A), 22.1–25.7 (B), and 27.1–29.7 (C).

3.2. Fitting with Improved Model Spectra

As Pravdo et al. (1978) and Tanaka (1986) suggested that the high-energy cut offs in X-ray pulsar spectra are formed by cyclotron resonant absorption in the intense pulsar magnetic field. In order to employ this idea as an improved model for the pulsar spectrum, we introduce the function

$$H_{\mathrm{CA}}\,(E) = DE^2/\,[\,(E - E_{\mathrm{a}})^2 + W^2\,], \tag{5}$$

and substitute it for $H(E)$ of equation (3) (Tanaka 1986). This approximates the optical depth of the cyclotron resonance scattering in a uniform magnetic field B (Herold 1979), where D is the Thomson opacity at $E \gg E_{\mathrm{a}}$; W is an artificial broadening and E_{a} is the (non-relativistic) electron cyclotron energy, given as

$$E_{\mathrm{a}} = 11.6\ (B/10^{12}\ \mathrm{Gauss})\ \ \mathrm{keV}. \tag{6}$$

Thus, this model involves a total of six free parameters. We applied this new model to the spectra of X0331+53, Her X-1 and Cen X-3. As presented in figure 4 and table 2,

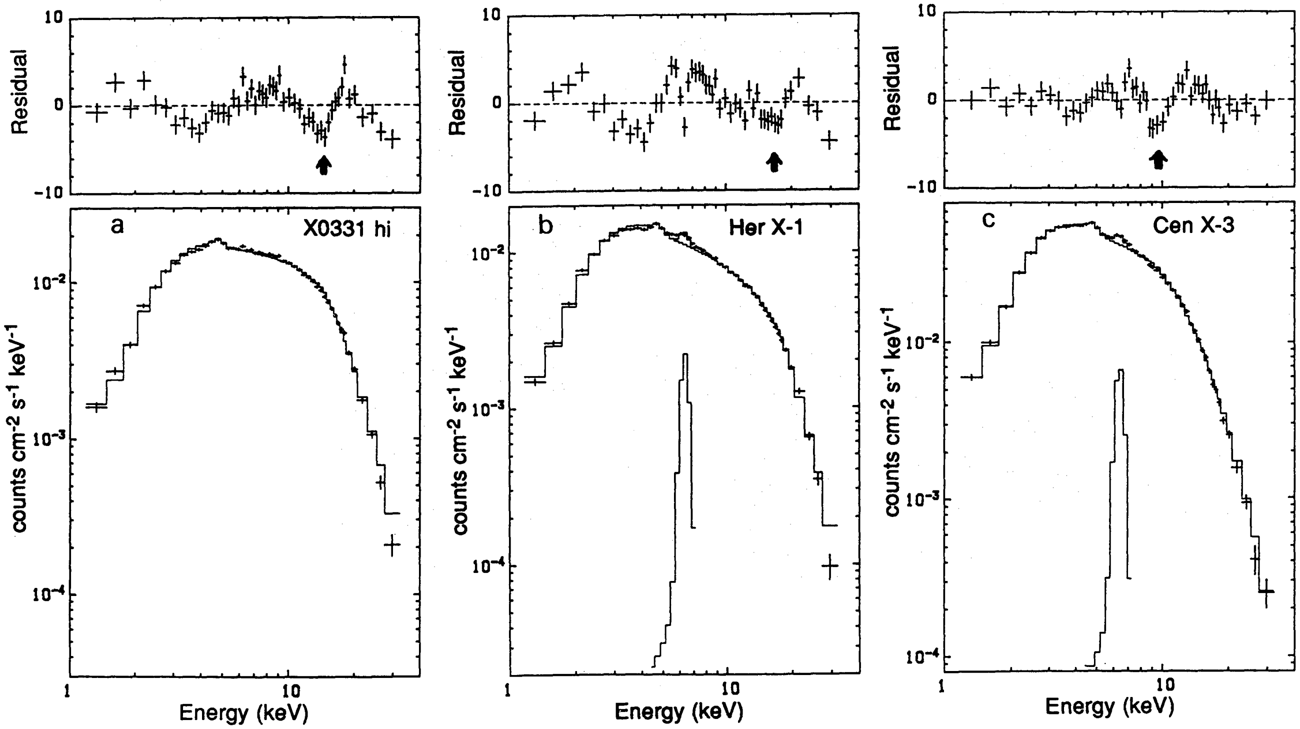

Fig. 3. Fits of X-ray pulsar spectra observed with the Tenma GSPC, using the power-law times exponential cutoff model. The results are summarized in table 1. (a) X0331+53 (spectrum A in figure 2). (b) Her X-1 observed on 1983 May 22 (Ohashi et al. 1984). (c) Cen X-3 observed on 1983 April 4. The upper panels show fit residuals in units of standard deviation, and the arrows indicate the cutoff energy, E_C.

Table 1. Results of spectral fitting with a power-law times exponential cutoff model.[a]

Physical quantity	Spectrum			
	X0331 high	X0331 medium	Her X-1	Cen X-3
Date of observation (1983)	Nov. 16–17	Nov. 22–25	May 22	April 4
Power-law normalization[b]	4.83±0.07	1.61±0.15	5.86±0.03	22.1 ±0.04
Spectral photon index α	0.51±0.02	0.77±0.04	0.88±0.02	0.92±0.03
Fe-line equivalent width (eV)[c]	–	–	150±18	140±20
Start of cutoff E_C (keV)	14.6 ±0.3	16.4 ±0.6	17.7 ±0.5	9.4 ±0.4
Cutoff steepness E_F (keV)	10.2 ±0.5	8.3 ±1.1	9.5 ±0.9	9.6 ±0.5
Absorption log N_H (cm^{-2})	22.1 ±0.1	22.2 ±0.1	21.8 ±0.1	21.9 ±0.1
Reduced chi-squared	4.23	2.09	6.16	2.77
Degrees of freedom	45	45	44	44

[a] Errors refer to single-parameter 90% confidence limits.

[b] In units of 10^{-2} counts cm^{-2} s^{-1} keV^{-1}.

[c] Modeled as a narrow (0.1 keV FWHM) Gaussian line with line-center energy fixed at 6.4 keV.

the fit has been systematically and significantly improved at least for three of the four spectra. The fit is still unacceptable in some cases, though the remaining problems are found elsewhere, rather than in the energy range above 10 keV. In section *5.1*, we discuss these results in detail.

3.3. Low-Energy Absorption

The absorption column during the peak outburst was $\sim 7 \times 10^{21}$ cm^{-2} (table 2), although it may increase toward the later phases of the outburst. On the other hand, the optical extinction indicates an interstellar absorption of $N_H = (1.3 \pm 0.3) \times 10^{22}$ cm^{-2} (CCV86), assuming a normal gas-to-dust ratio. It is, therefore, inferred that the observed X-ray absorption is mostly of interstellar origin and that the circumstellar contribution is small ($< 7 \times 10^{21}$ cm^{-2}). This result constrains the circumstellar matter density: if we assume the simplest (but possibly unrealistic) case of an isotropic stellar wind of constant velocity surrounding the pulsar, a simple geometrical argument shows that the wind density near the pulsar must satisfy

$$n \leq N_H/a \sim 1 \times 10^9 \text{ cm}^{-3}. \qquad (7)$$

Here, $a \sim 6 \times 10^{12}$ cm is the binary separation based on the observed $a_x \sin i = 48$ lt-s (S85) and $i \sim 15°$ (CCV86), with a_x being the pulsar's orbital semi-major axis and i the orbital inclination (S85; Iye and Kodaira 1985; CCV86).

3.4. Iron Line Emission

The Tenma GSPC has established the presence of narrow iron K-emission lines at about 6.4 keV in the spectra of many massive galactic X-ray binaries (Inoue 1985;

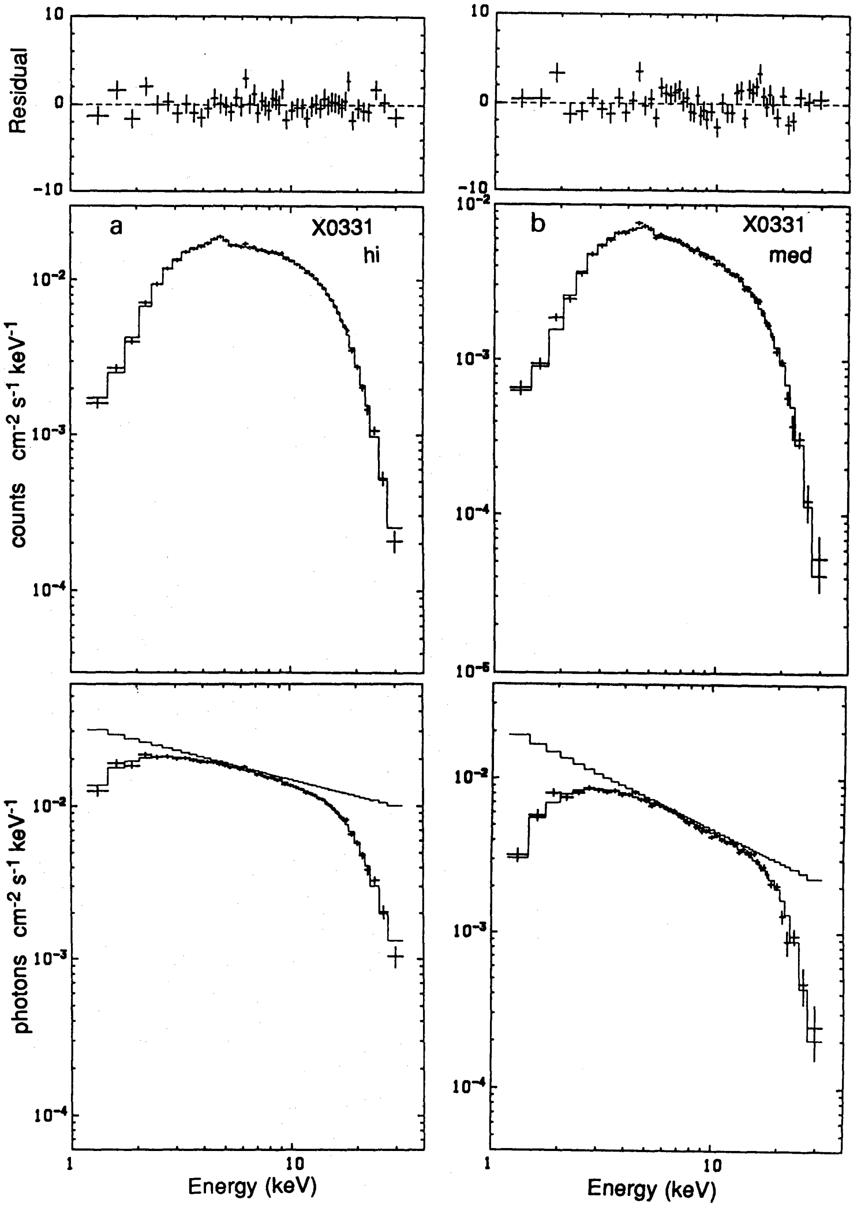

Fig. 4. X-ray pulsar spectra fitted with the power-law times cyclotron absorption formula (see text). Best-fit parameters are summarized in table 2. Panels (a), (c), and (d) refer to the same spectra as those in figure 3, while (b) corresponds to spectrum B in figure 2. Bottom panels show the inferred incident spectra.

Makishima 1986; Nagase 1989). The iron lines are thought to be produced by cool matter in the system, through fluorescent reprocessing of continuum X-rays. The fluorescence may take place in various regions in the system, including the primary's photosphere, the stellar wind, and matter local to the neutron star (Sato et al. 1986; Nagase 1989).

The spectra of X0331+53, however, exhibit no iron line feature. The improved

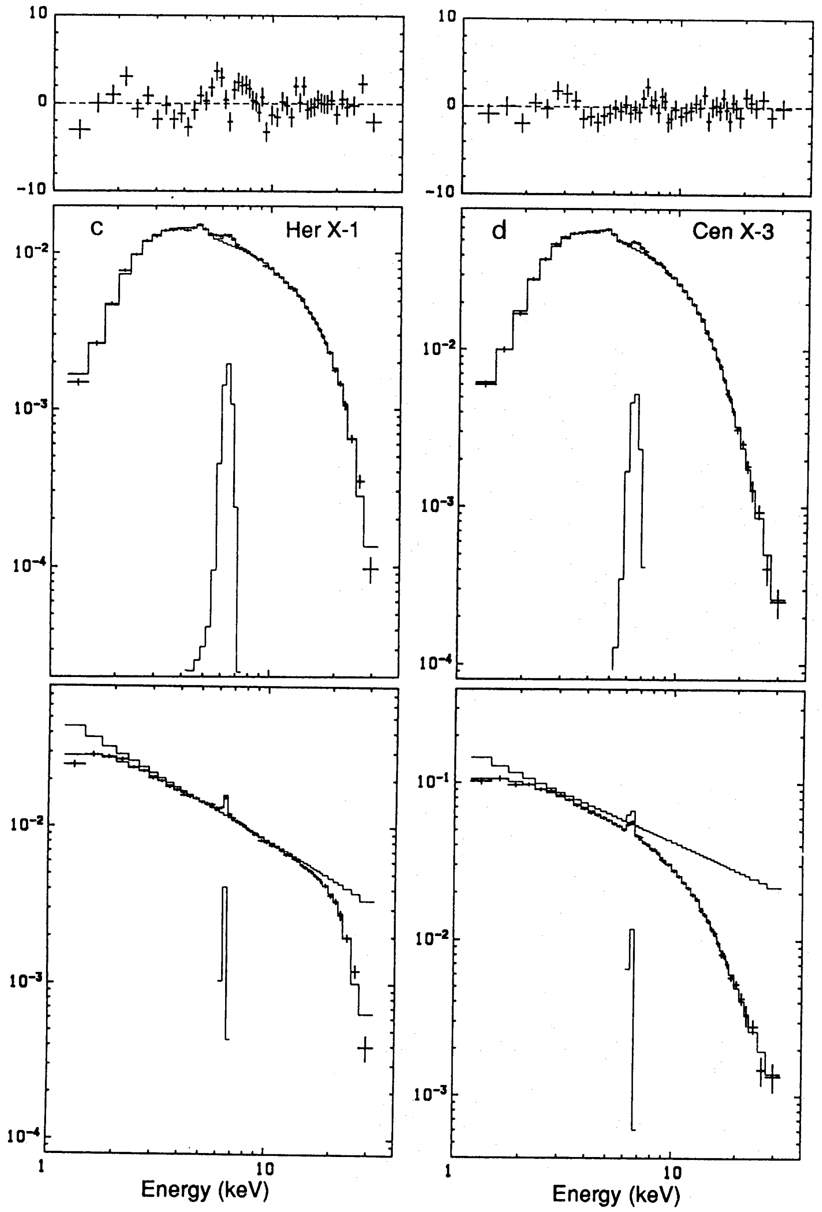

Fig. 4 (continued)

spectral model [equation (5)] has constrained the equivalent width (EW) of a 6.4 keV narrow line to be < 30 eV (90% confidence). This requires the column density of the stellar wind to be $< 3 \times 10^{22}$ cm^{-2} (White and Swank 1984; Inoue 1985; Makishima 1986), if it is spherically symmetric around the pulsar. For anisotropic matter distributions, the EW reflects the direction-averaged matter density rather than the line-of-sight column. In any case the absence of the iron line flux is consistent with equation (6), giving independent evidence of a relatively small circumstellar matter density.

Table 2. Results of spectral fitting with the cyclotron absorption model.[a]

Physical quantity	Spectrum			
	X0331 high	X0331 medium	Her X-1	Cen X-3
Power-law normalization	4.47±0.12	1.47±0.06	5.80±0.05	29.4±2.6
Spectral photon index α	0.37±0.03	0.68±0.04	0.82±0.02	0.61±0.09
Fe-line equivalent width (eV) ...	–	–	135±20	140±30
Thomson opacity D	0.28±0.11	0.12±0.07	0.05±0.01	1.8 ±1.1
Cyclotron energy E_{a} (keV)	28(+15,−4)	29(+21,−6)	28(+17,−4)	17(+15,−4)
Broadening W (keV)	11±5	6±2	5±1	21±7
Absorption log N_{H} (cm^{-2})	21.8 ±0.1	22.2±0.2	21.6 ±0.1	21.4 ±0.3
Reduced chi-squared	1.27	2.06	2.88	1.10
Degrees of freedom	44	44	43	43

[a] Conditions are the same as table 1.

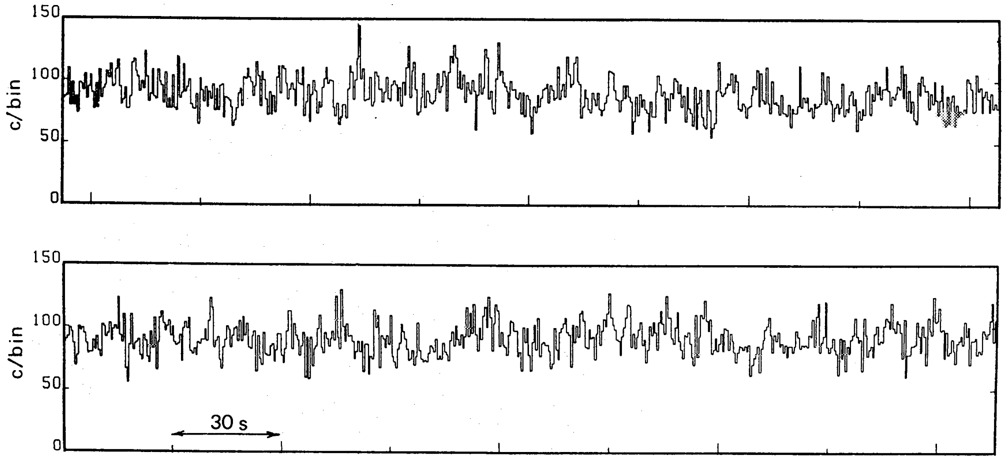

Fig. 5. An example of the 2–30 keV X-ray count record from X0331+53 with a 0.5-s binning, showing a rapid flickering behavior.

4. X-Ray Variability

4.1. Rapid X-Ray Fluctuations

Figure 5 is an example of a raw count-rate record for X0331+53, showing random rapid X-ray variability. The average properties of this variability can be represented by the ensemble-averaged Fourier power-density spectra (PDS) for the count-rate time series, as shown in figure 6. In this form of PDS, the fundamental and the 2nd harmonic of the 4.4-s coherent pulsations are barely visible. With the Poisson noise component subtracted, the PDS is roughly "white" up to a characteristic frequency, $f_{\mathrm{k}} \sim 0.1$ Hz,

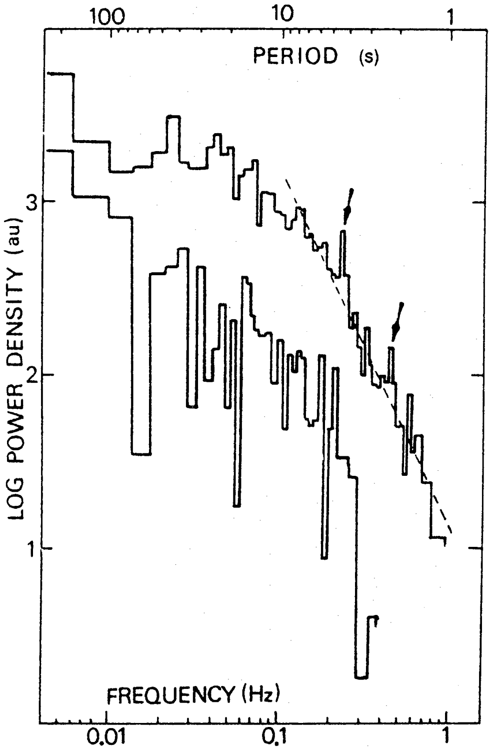

Fig. 6. Fourier power-density spectra of 2–12 keV X-ray count-rate data from X0331+53, for the outburst peak (top histogram; November 15.5–17.6) and declining phase (lower histogram; November 22.5–26.4). They were calculated as incoherent superpositions of 40 and 22 individual power-density spectra, respectively, each based on 256-s long data streams. The white-noise component, due to photon statistics, has been subtracted. The 4.4-s pulsation and its 2nd harmonic are indicated by arrows. The dashed line indicates a slope of γ=2.0.

beyond which it falls off with a roughly constant logarithmic slope of $\gamma \sim 2$. Above $\sim$1 Hz, the PDS becomes rather uncertain due to poor statistics.

We computed the fractional rms amplitude of the intrinsic variation by integrating the white-noise-subtracted PDS over the 0.01–1 Hz frequency range, and normalizing its square root to the average source intensity. The rms amplitude, thus found, is $\sim$25%, and no dependence was observed either on the X-ray energy or the average source intensity. This rules out the possibility that the variability could be caused by a fluctuating absorbing screen.

We also calculated the X-ray cross-correlation functions (CCFs) between count rates in different energy bands. Figure 7 is an example of the CCF between the 1.7–8.1 keV and 8.1–18.5 keV bands. We find no evidence for any time lag within the limits set by the 0.125-s time resolution. However, the slightly asymmetric shape of the CCF suggests a possible existence of some kind of lag between fluctuations in the two energy bands, such as has been observed in Cyg X-1 (Miyamoto et al. 1988). We found that the variations in the 1.7–8.1 keV and 8.1–18 keV bands are fairly well ($\geq$ 65%) correlated.

We note that X0331+53 shares most of these properties of aperiodic X-ray vari-

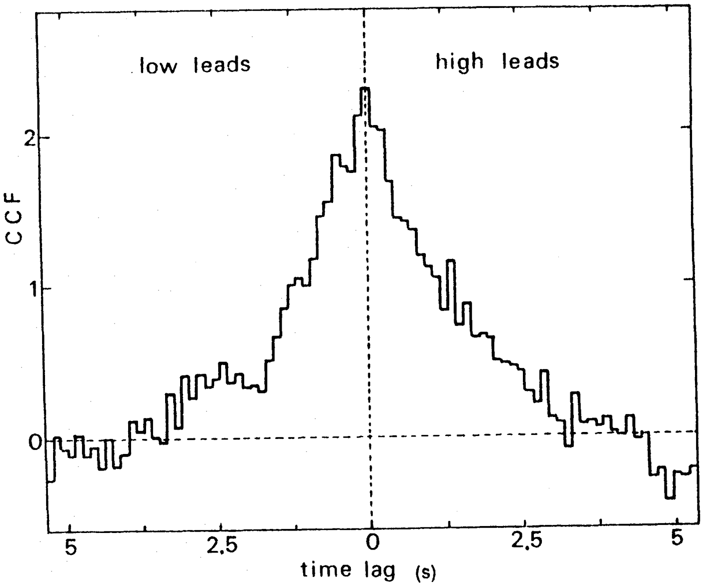

Fig. 7. The cross-correlation function (in arbitrary unit) between count rates in the 1.7–8.1 keV and the 8.1–18.5 keV energy bands, calculated for a 256-s long time series with a 0.125-s time resolution.

ability with Cyg X-1 and GX 339−4. In fact, Cyg X-1 has $f_{\mathrm{k}} \sim 0.1$ Hz and $\gamma = 1.0-1.7$ (Liang and Nolan 1984; Makishima 1988), while GX 339−4 has $f_{\mathrm{k}} \sim 0.2$ Hz and $\gamma \sim 1.7$ (Maejima et al. 1984). However, the rms variation of X0331+53 may be somewhat smaller than those of Cyg X-1 and GX 339−4 (~30%).

4.2. The 4.4-s Pulsation

Following the discovery of the 4.4-s coherent pulsations with EXOSAT (*IAU Circular*, No. 3902, 1983; S85), we confirmed them using the Tenma data. As shown in figure 8, the heliocentric pulsation periods, thus determined, are consistent with a prediction based on the orbital solution of S85. In the hope of independently examining the orbital parameters, we attempted a pulse arrival-time analysis. However, due to the shallow pulse amplitude, we could detect X-ray pulses only when the source intensity was ≥ 15 counts s^{-1} (and hence only in the November observations). Interruptions in data coverage also made it difficult to track the pulse phase coherently. We therefore could not derive meaningful constraints on the orbital parameters of X0331+53.

Figure 9 shows folded pulse profiles obtained on two occasions. Thus, the pulse fraction is only 10–15% peak-to-peak, or 4–6% rms, which is much smaller than the random variation. The pulse profile was generally single-peaked, but occasionally became double-peaked. The suggested correlation between the X-ray intensity and the pulse profile (S85) was not apparent in the Tenma data. The pulse fraction did not change significantly as the mean X-ray intensity decreased by a factor of 3. No noticeable energy dependence was found, neither in the pulse fraction nor in the pulse profile.

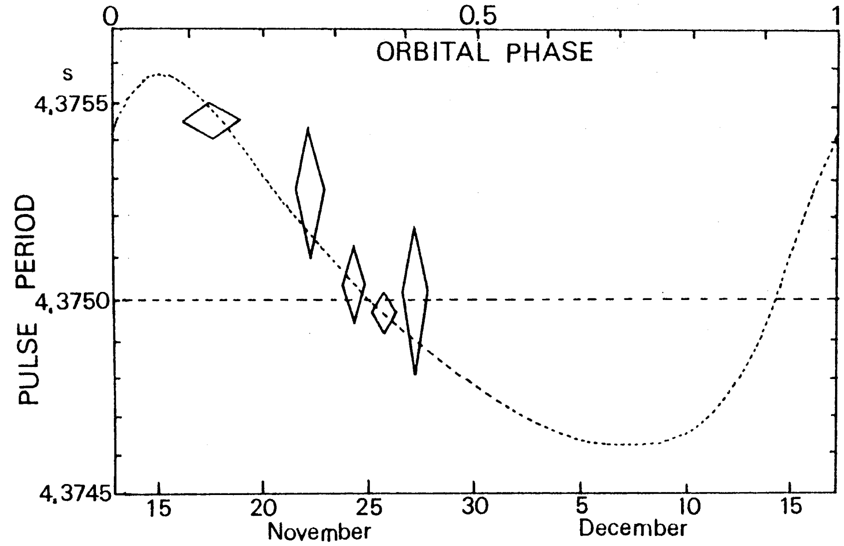

Fig. 8. Heliocentric pulse periods of X0331+53 determined with Tenma (diamonds). The dotted curve is the Doppler modulation predicted by the EXOSAT orbital solution (S85), assuming an intrinsic pulse period of $P = 4.3750$ s.

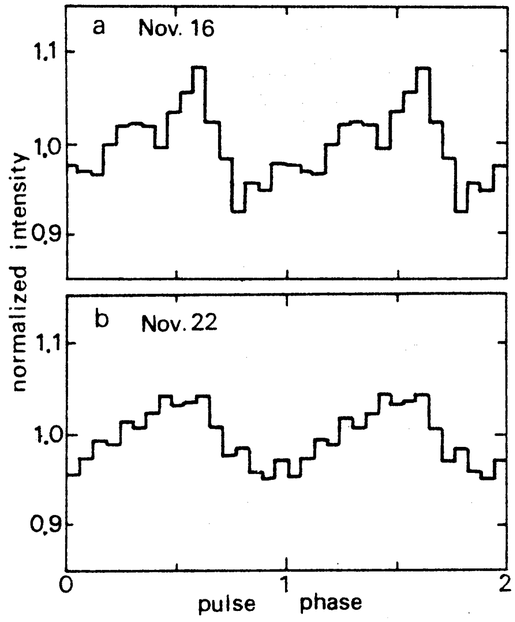

Fig. 9. Folded 2–20 keV pulse profiles of the 4.4-s pulsation, observed on November 16 (panel a) and 22 (panel b). The background has been subtracted.

5. Discussion

5.1. *X-Ray Spectra*

There are two outstanding characteristics specific to the spectra of X-ray pulsars. One is a spectral feature attributed to cyclotron absorption or emission, observed from Her X-1 [either absorption at 32–38 keV or emission at 52 keV; Voges et al. (1982); Soong et al. (1988)], 4U 0115+63 [at 20 keV; Wheaton et al. (1979); White et al. (1983)], and recently from 4U 1538−52 [absorption at 20 keV; Clark et al. (1989); Nagase (1989)] and from gamma-ray bursts [absorption at 20 and 40 keV; Murakami et al. (1988)]. The other is a clear spectral break, seen at 10–20 keV in power-law-like continua (White et al. 1983). We assume, after Pravdo et al. (1978) and Tanaka (1986), that these two characteristics are manifestations of the same phenomenon, namely the cyclotron resonance which is expected to dominate the interaction between matter and radiation in the accretion column of pulsars. In fact, theoretical studies by Bonazzola et al. (1979) and by Mészáros and Nagel (1985a, b) show that cyclotron resonance is likely to cause absorption, rather than emission, at $E_{\rm a}$, accompanied by a clear spectral steepening above $\sim E_{\rm a}/2$.

One piece of observational evidence in support of this interpretation is the fact that the value of $E_{\rm C}$ in equation (4) is found to be relatively independent of the luminosity or pulse phase in many pulsars (e.g., table 1), suggesting that the spectral break reflects properties intrinsic to each pulsar. Further support comes from observations of the peculiar 6.9-s pulsar X2259+586 with an unusually steep 2–10 keV spectrum, inferred to have a weak magnetic field [$(5\text{–}8)\times 10^{11}$ G] from timing studies (Koyama et al. 1987; Hanson et al. 1988). It also exhibits a possible spectral feature at 6–8 keV (Koyama et al. 1989; Nagase 1989). We can, then, interpret this pulsar as having $E_{\rm a}$=5–7 keV [see equation (6)]; we thus observe a steeply falling spectrum between $E_{\rm C} \sim E_{\rm a}/2$ and $E_{\rm a}$.

We have introduced equation (5) to describe the cyclotron absorption model. This model can provide a unified description of the 8–28 keV spectra of 4U1538−52 obtained with Ginga (Clark et al. 1989), which exhibit absorption features at 20 keV and cutoffs at ~15 keV (Nagase 1989). We have shown that this model provides systematically better fits than equation (4) to the spectra of X0331+53, Her X-1 and Cen X-3. The values of $E_{\rm a}$, thus obtained, are reasonable for the surface field of a pulsar; in particular, the range of $E_{\rm a}$ determined for Her X-1 includes the value $E_{\rm a} =$ 32–38 keV, which was directly measured in hard X-rays by the detection of absorption features (Voges et al. 1982; Soong et al. 1988). The two spectra of X0331+53 gave similar values of $E_{\rm a}$, and the brighter spectrum gave larger values of D and W, as well as a flatter continuum. This can be interpreted as showing that the value of $E_{\rm a}$ is specific to each pulsar, while other spectral parameters are luminosity dependent. Thus, equation (5) is physically meaningful and self-consistent. In terms of this model, X0331+53 is inferred to have a spectrum typical of X-ray pulsars, and a magnetic field strength of $\sim 3 \times 10^{12}$ G from equation (6).

The values of $E_{\rm a}$ are, however, not very well determined from the present study alone. This is not surprising because none of our raw spectra show a clear absorption feature, and the inferred values of $E_{\rm a}$ are mostly outside or at the highest end of our spectral range. In addition, the three parameters ($E_{\rm a}, W,$ and D) strongly couple with each other. Similarly, we admit that equation (5) is a very crude approximation, neglecting photon polarization, electron momentum distribution, and complex radiative transfer in the accretion column. Also, the present form of broadening (W) might not be appropriate. (In fact, the absorption "trough" has been smeared away in the fit for Cen X-3 due to the large value of W). The assumption of a single power-law continuum may not be realistic, either. We therefore claim neither the detection of cyclotron resonance features in these pulsars, nor the determination of their surface field strengths. Our emphasis is that equation (5) can fit the observed spectra very well.

5.2. Nature of the Rapid Aperiodic Variability

The most striking feature of X0331+53 is the aperiodic X-ray fluctuation, which persisted throughout the outbursts with roughly constant properties. This phenomenon, therefore, seems to be intrinsic to the X-ray emission from this object, rather than a transient phenomenon. There are two alternative explanations for the detection from X0331+53 of this type of variability, which had not previously been observed in other pulsars. One interpretation is that the fluctuations are unique to X0331+53 and, hence, reflect some anomaly in the physical properties of this source. The other is to assume that the rapid X-ray fluctuation is common among X-ray pulsars, but is usually masked in the X-ray data by the strong periodic pulsations.

The first alternative requires us to determine exactly what is anomalous with X0331+53. A Be star and a magnetized neutron star is, however, a common combination, and the X-ray luminosity of X0331+53 is ordinary. It seems difficult as well to assume that the mass and/or radius of the neutron star in X0331+53 is anomalous, since it is not obvious how such an anomaly could lead to the observed variation. Also, our spectral analysis indicates that the magnetic field intensity of the neutron star in X0331+53 is $\sim 3 \times 10^{12}$ G, quite typical for a pulsar. Thus, the first alternative may not be very promising.

We next consider the second alternative. It is not trivial to examine the aperiodic power distribution in the PDS of X-ray pulsars. This is because the intense higher harmonics of the periodic pulsations couple with slow amplitude and/or shape modulation, thus producing a spurious continuum in the PDS up to frequencies much higher than that of the pulsations (Makishima 1988; cf. Hasinger 1988). This difficulty may be avoided by studying pulsars with small pulse fraction and/or very long pulse periods. Recently, aperiodic variability with $\gamma \sim 1.4$ has been discovered in several X-ray pulsars, including GX 301$-$2 and GX 1+4 (Makishima 1988). This encourages the second standpoint, although the observed rms amplitudes of variation in these pulsars (typically $\sim$10%) are smaller than that of X0331+53.

Thus, we tentatively suggest that rapid variations are a common phenomenon in accreting X-ray pulsars, and that they have manifested themselves in the case of X0331+53 mainly because of the weakness of the pulsations. The low amplitude of the pulsations from X0331+53 may result because the pulsar is observed at a nearly pole-on inclination, as suggested by the small systemic inclination ($i \sim 15°$; CCV86), and/or because the neutron star in X0331+53 is a nearly coaligned rotator.

The exact origins of the random variations of X0331+53 are yet to be discovered. In particular, we must discover how and where the variability is produced, and what determines the basic properties of the variations including γ, f_{k}, and the rms amplitude. Also, we must eventually clarify whether the variability of this source is produced by the same mechanism as is operative in Cyg X-1 and GX 339−4. Although these problems are beyond the scope of this paper, we suggest that aperiodic variability with $\gamma = 1 - 2$ is a common phenomenon among accreting compact objects (Makishima 1988).

5.3. Problems with Direct Wind Accretion

There is now little doubt that X0331+53 is a binary composed of a Be-star and a magnetized neutron star. The primary, with its estimated radius ($\sim 5 \times 10^{11}$ cm) much smaller than the orbital separation ($a \sim 6 \times 10^{12}$ cm), is far from Roche-lobe filling. This has led Stella et al. (1986) to assume that the system is powered by the direct capture of an ordinary stellar wind from the primary. They also combined this picture with the idea of "centrifugal drag" to explain the large intensity modulation associated with the orbital motion.

The Be-pulsars are, however, in some respects different from "genuine" wind-fed massive binaries (WFMBs; e.g., Vela X-1). The positive correlation between the pulsation and orbital periods, found in the former (Corbet 1986), is absent in the latter pulsars. Wind-fed pulsars can both spin up and down during accretion (Nagase et al. 1984a, b; Corbet 1986), while Be-pulsars often spin up during outbursts (Li et al. 1979; Ricketts et al. 1981; Nagase et al. 1982; Parmar et al. 1989) although the case for X0331+53 is unclear.

X0331+53 is further distinguished from WFMBs by several points. The large variations in intensity and absorption exhibited by WFMBs, on time scales of minutes to hours (White and Swank 1984; Nagase et al. 1984b; Gottwald et al. 1986), are absent (<20%) in X0331+53. The circumstellar absorption in the WFMBs often amounts to 10^{23-24} cm^{-2} (Dupree et al. 1980; White et al. 1983; Nagase et al. 1986; Nagase 1989), while that in X0331+53 is $<10^{22}$ cm^{-2}. Yet the luminosities of the WFMBs are at most comparable to, and often lower than, that of X0331+53. The P-Cygni profiles, indicative of a strong stellar wind (e.g., Parkes et al. 1980; Dupree et al. 1980), did not persist in the optical spectra of BQ Cam (Bernacca et al. 1984; Stocke et al. 1985; Kodaira et al. 1985; CCV86). Thus, X0331+53 shows no evidence for the strong stellar wind that would be required in the picture of Stella et al. (1986).

To be more quantitative, let us assume a stellar wind of density $n = n_9 \times 10^9$ cm^{-3} and velocity $v = v_8 \times 10^8$ cm s^{-1} relative to the pulsar. The standard wind accretion theory (Davidson and Ostriker 1973; Lamers et al. 1976) predicts a mass accretion rate of

$$M_{\mathrm{a}} = 4\pi G^2 m n M_{\mathrm{x}}^2 v^{-3} = 8.8 \times 10^{14} n_9 v_8^{-3} \mathrm{~g~s^{-1}} \tag{8}$$

Here, $M_{\mathrm{x}} = 1.4 M_\odot$ is the pulsar mass and $m = 1.2 m_{\mathrm{p}}$ is the mean particle mass of accreting matter. We can also estimate M_{a} from equation (2), to be

$$M_{\mathrm{a}} = 1.6 \times 10^{16} (d/3 \mathrm{~kpc})^2 \mathrm{~g~s^{-1}}, \tag{9}$$

assuming 10 km for the pulsar radius and an efficiency of unity for gravitational to X-ray energy conversion. From these two equations, we obtain

$$v = 3.8 \times 10^7 \, n_9^{1/3} \, (d/3 \text{ kpc})^{-2/3} \text{ cm s}^{-1}. \tag{10}$$

On the other hand, the orbital velocity of the pulsar V is given as

$$V = 1.4 \times 10^7 \, (M_0/10M_\odot)^{1/2} (a/200 \text{ lt-s})^{-1/2} \text{ cm s}^{-1}, \tag{11}$$

where M_0 is the primary mass (Kodaira et al. 1985). In view of equation (7), v and V are thus already quite close together. Therefore, the intrinsic wind velocity w cannot be very large (e.g., $w \le 3 \times 10^7$ cm s^{-1}), because of the relation $v^2 = V^2 + w^2$. This value of w is significantly smaller than the typical stellar wind velocities from massive stars, (1–3)$\times 10^8$ cm s^{-1} (e.g., Lamers et al. 1976); thus, the self-consistency of the wind capture hypothesis (S85) is not obvious.

5.4. Accretion from a Be Star Envelope

Instead of the wind-capture hypothesis, we assume after CCV86 that X0331+53 was fueled by mass accretion from a circumstellar envelope around BQ Cam. The gas envelope, evolving on the time scale of years, is indeed one of the most important features of Be stars (Poeckert 1982). Accretion from such envelopes has been discussed by Maraschi et al. (1976), Shibazaki (1982), Charles et al. (1983) and Apparao (1985), as a model for hard X-ray transients. The infrared excess of BQ Cam in 1983–1984 followed by a gradual decline (Coe et al. 1987), as well as long-term Hα variability (Iye and Kodaira 1985), strongly suggests that the envelope developed around BQ Cam during the period of X-ray activity and then gradually disappeared (CCV86).

Although the detailed geometry is still uncertain (Poeckert 1982), the Be-envelopes may extend to several stellar radii along the rotational equatorial plane of the Be star, possibly in near-Keplerian rotation. This ensures small values of v and, hence, high values of M_a [equation (8)], even for relatively small values of n. If the envelope is confined within a finite volume, the circumstellar absorption column will be small, as has been observed. Also, in that case, the moderate orbital eccentricity ($e = 0.31$ for X0331+53; S85) will make the envelope fill up the critical potential lobe only in a limited phase of the pulsar's orbit near the periastron passage (Charles et al. 1983), accounting for a large orbital modulation in the luminosity. When an envelope develops, such that it fills the potential lobe over the whole orbit, the orbital modulation may diminish, like in the extended flare of X0331+53 in 1973 (Terrell and Priedhorsky 1984) and those of 4U 0115+63 (Rose et al. 1979; Kriss et al. 1983).

As a consequence of this picture, we expect a stable accretion disk to form around a Be-pulsar during outbursts (Corbet 1986), due to the small radial velocity of the matter (Wang 1987; Matsuda et al. 1987). Then, the Be-pulsars may obtain a larger net torque from the infalling matter, compared with wind-fed pulsars, which are most likely to lack an accretion disk. This, in turn, may explain the difference in spin-period changes between the wind-fed and the Be-type pulsars. Also, the formation of an accretion disk may account for the reduced medium-time-scale X-ray variability of the Be-pulsars (including X0331+53) and disk-fed pulsars (Cen X-3, Her X-1, etc.).

In short, the Be-envelope scenario can explain many of the observed features of X0331+53 much more naturally than the wind-capture scenario, on the condition that the envelope has a finite radial extent. However, our scenario does not exclude a mechanism for "centrifugal inhibition of accretion" (Stella et al. 1986) to be operative at the same time.

6. Summary

(1) Using Tenma, we observed two outbursts from the 4.4-s transient X-ray pulsar X0331+53. The measured X-ray flux, luminosity, spectra and pulse periods are in good agreement with those obtained with EXOSAT (S85).

(2) We have used an improved formula to model the spectra of accreting X-ray pulsars, based on a simplified expression for the cyclotron scattering cross section. It can describe the spectra of X0331+53 and other pulsars much better than the exponential cutoff model. Using this model, X0331+53 is suggested to have a magnetic field strength of $\sim 3 \times 10^{12}$ G.

(3) Although the exact origin of the rapid X-ray fluctuation is still unknown, we prefer the interpretation that this type of variability is a rather common phenomenon in accreting compact objects, both neutron stars and black holes.

It is likely that the small pulse fraction of X0331+53 made the random variations easier to detect than in other pulsars.

(4) We have argued that X0331+53 was more likely to be powered by accretion from an equatorial envelope around the possibly Be-type primary, rather than by capturing the stellar wind.

Note added in proof: The suggested cyclotron absorption feature of X0331+53 has been confirmed at 28.5 keV with the Ginga observatory in October 1989, during another outburst of the source (*IAU Circular*, No. 4858, 1989).

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