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Pulse-Period Changes of X-Ray Pulsars Measured with Hakucho and Tenma

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Abstract

Eight X-ray pulsars, Her X-1, Cen X-3, 4U 1626−67, OAO 1657−415, A 0535+26, Vela X-1, 4U 1538−52, and GX 301−2, have been observed from Hakucho and Tenma. The pulse periods of all these X-ray pulsars measured with Hakucho and Tenma between March 1979 and October 1983 are summarized together with those of 4U 1700−37 and 4U 1907+09, the pulsations of which were newly discovered by Tenma observations. Several instances of remarkable behavior in pulse-period change are revealed both for the wind-fed and disk-fed pulsars.

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

1. Introduction

Among as many as a hundred bright galactic X-ray sources, twenty-three sources have been classified as X-ray pulsars. The pulse profiles, the energy spectra, the pulse periods, the orbital elements, and the optical companions of these X-ray pulsars have been extensively investigated by many authors (Rappaport and Joss 1983; White et al. 1983 and references therein). Since March 1979, several X-ray pulsars have been observed by the Japanese

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X-ray astronomy satellites Hakucho and Tenma, and the histories of the pulse-period change have been studied.

We observed six X-ray pulsars from Hakucho, Her X-1, Cen X-3, 4U 1626−67, A 0535+26, Vela X-1, and GX 301−2 on several occasions between March 1979 and October 1983. Some of the results were summarized by Hayakawa and Nagase (1982). Some results on Cen X-3, A 0535+26, and Vela X-1 have also been published by Murakami et al. (1983), by Nagase et al. (1982), and by Nagase et al. (1981, 1984), respectively.

From Tenma, launched on February 20, 1983, we observed seven X-ray pulsars, Her X-1, Cen X-3, 4U 1626−67, OAO 1657−415, A 0535+26, Vela X-1, and 4U 1538−52, over eight months from March 1983 to October 1983. Pulsations in two massive X-ray binaries, 4U 1700−37 and 4U 1907+09, were discovered by observations with the gas scintillation proportional counters (GSPC) on board Tenma.

In the present paper we briefly summarize the pulse periods of these pulsars measured with the two satellites over the last four and a half years. The results reveal remarkable features of the pulse-period change.

The earlier observations of Vela X-1 with Hakucho revealed the secular spin-down of the pulse period (Nagase et al. 1981; Nagase 1981). Later observations of Vela X-1 from December 1981 to December 1982 with Hakucho indicated that the average spin-down trend had ceased and the pulse period became nearly constant (Nagase et al. 1984). This is confirmed by the Tenma observation.

Another important result is a spin-down of Her X-1 which has recently started in contrast to its average spin-up trend observed before 1980. The pulse period of Cen X-3 also exhibits a significant wavy fluctuation around the average trend of secular spin-up. In contrast to the complex behavior of pulse period observed between 1975 and 1977, recent observations of A 0535+26 have suggested a secular decrease in the pulse period. Short-term variations of pulse period have been measured during the observations of several X-ray pulsars, such as Cen X-3, Vela X-1, and GX 301−2. Except for the low-mass binary X-ray pulsar 4U 1626−67, the other X-ray pulsars observed do not follow a steady spin-up.

These pulse-period changes are considered to be of great interest in diagnosing physical properties of the circumstellar plasma and possibly the internal structure of the neutron star. However, in the present paper we will not go too far into theoretical aspects of the pulse-period change but concentrate on observational results.

2. Observations and Results

All the pulse periods measured with Hakucho and Tenma between March 1979 and October 1983 are listed in table 1 together with the dates of observations. Here and hereafter the heliocentric pulse periods are used. All the quoted uncertainties in the table and hereafter in the text are signle parameter 1σ confidence limits, unless otherwise mentioned. The X-ray detectors used in the present studies are a Xe-filled proportional counter (FMC-2, Kondo et al. 1981) for the Hakucho observations and a set of GSPC (Tanaka et al. 1984; Koyama et al. 1984) for the Tenma observations. The observations of Vela X-1 with Hakucho and the pulse periods obtained thereby are described separately by Nagase et al. (1984), and are excluded from the table. The pulse-timing data of Cen X-3 measured in March 1981 (Murakami et al. 1983) are combined with those observed in March 1982 and in April 1983 for the pulse-timing analysis as listed in table 1. The result on A 0535+26 observed in October 1980 (Nagase et al. 1982) is also listed in table 1, for comparison with the recent results by Hakucho.

Table 1. Pulse periods of X-ray pulsars measured with Hakucho (H) and Tenma (T).

Source name	Observation Year/Month/Day	Pulse period[a] P_0 (s)	Time derivative of pulse period $\dot{P}$ (s s^{-1})
Her X-1[b] ········	1982/ 6/13-17(H)	1.2377939 ±0(1)[c]	$(1.0\pm0.6)^{c}\times10^{-12}$
	1983/ 5/21-26(T)	1.23779422±0(1)	—
Cen X-3[b] ········	1981/ 3/21-26(H)	4.8317261 ±0(1)	$(-1.2\pm0.2)\times10^{-11}$
	1982/ 3/20-30(H)	4.8294492 ±0(4)	$(-13.8\pm0.1)\times10^{-11}$
	1983/ 4/ 4- 6(T)	4.8267224 ±0(5)	$(10\pm6)\times10^{-11}$
4U 1626−67 ······	1982/ 7/ 2- 6(H)	7.67271 ±0(3)	—
	1983/ 5/ 2- 6(T)	7.671350 ±0(3)	$(-1.3\pm0.4)\times10^{-10}$
OAO 1657−415····	1983/ 7/18-23(T)	37.885 ±0(1)	—
4U 1700−37[d] ······	1983/ 7/18-22(T)	67.4 ±0(1.5)	—
A 0535+26[d] ······	1980/10/ 2-11/3(H)	103.6471 ±0(3)	$(-8.43\pm0.05)\times10^{-8}$ [$\ddot{P}=(6.4\pm0.1)\times10^{-14}$ s^{-1}]
	1982/11/16-20(H)	103.423 ±0(3)	—
	1983/10/ 1-26(H, T)	103.3429 ±0(7)	$(-4.2\pm0.1)\times10^{-8}$ [$\ddot{P}=(-7.9\pm0.2)\times10^{-14}$ s^{-1}]
Vela X-1 ········	1979/ 3-1982/12(H)	(282.746-282.950)[e]	
	1983/ 3/ 3-18(T)	282.9306 ±0(3)	$(-5.3\pm0.3)\times10^{-9}$
4U 1907+09 ······	1983/ 8/29- 9/7(T)	437.485 ±0(5)	—
4U 1538−52 ······	1983/ 6/28- 7/6(T)	529.772 ±0(6)	—
GX 301−2[b] ······	1982/ 4/ 1-24(H)	697.63 ±0(5)	$(3.2\pm0.7)\times10^{-7}$
	1982/ 5/15-20(H)	698.34 ±0(4)	—

Notes:
[a] All listed values of pulse period are those at the beginning of observation.
[b] P and $\dot{P}$ for respective data sets are determined by the joint fit assuming orbital elements common to the two or three data sets.
[c] All quoted uncertainties are single parameter 1σ confidence limits.
[d] Apparent periods and their change rates during observations, including the orbital Doppler effect of period change.
[e] Fourteen pulse periods have been obtained for the interval [see Nagase et al. (1984)].

The present analysis also gives finite rates of intrinsic pulse-period change for some observations. The rates of short-term change of the pulse period are also listed in the last column of table 1.

Pulsation at 437.485±0.005 s of the 8.4-d binary X-ray source 4U 1907+09 (Marshall and Ricketts 1980; Schwartz et al. 1980) was discovered in the Tenma observation of August–September 1983. Pulse-timing analysis revealed the Doppler effect of pulse arrival time with a projected semimajor axis of about 95 light-s (Makishima et al. 1984). Murakami et al. (1984) also found pulsation of the eclipsing binary X-ray source 4U1700−37 (Branduardi et al. 1978). The pulsation with a period of 67.4±1.5 s was observable only in its flaring state. Detailed results of the Tenma observation of these two X-ray binaries are described separately by Makishima et al. (1984) and by Murakami et al. (1984), respectively.

Among those X-ray pulsars listed in table 1, the pulse periods of six X-ray pulsars, Her X-1, Cen X-3, 4U 1626−67, A 0535+26, Vela X-1, and GX 301−2, have been investigated by many X-ray astronomy satellites before Hakucho (Rappaport and Joss 1983). The results obtained by the Hakucho and Tenma observations are shown in figure 1 along with the previous results. In the figure, the present results obtained from Hakucho and Tenma

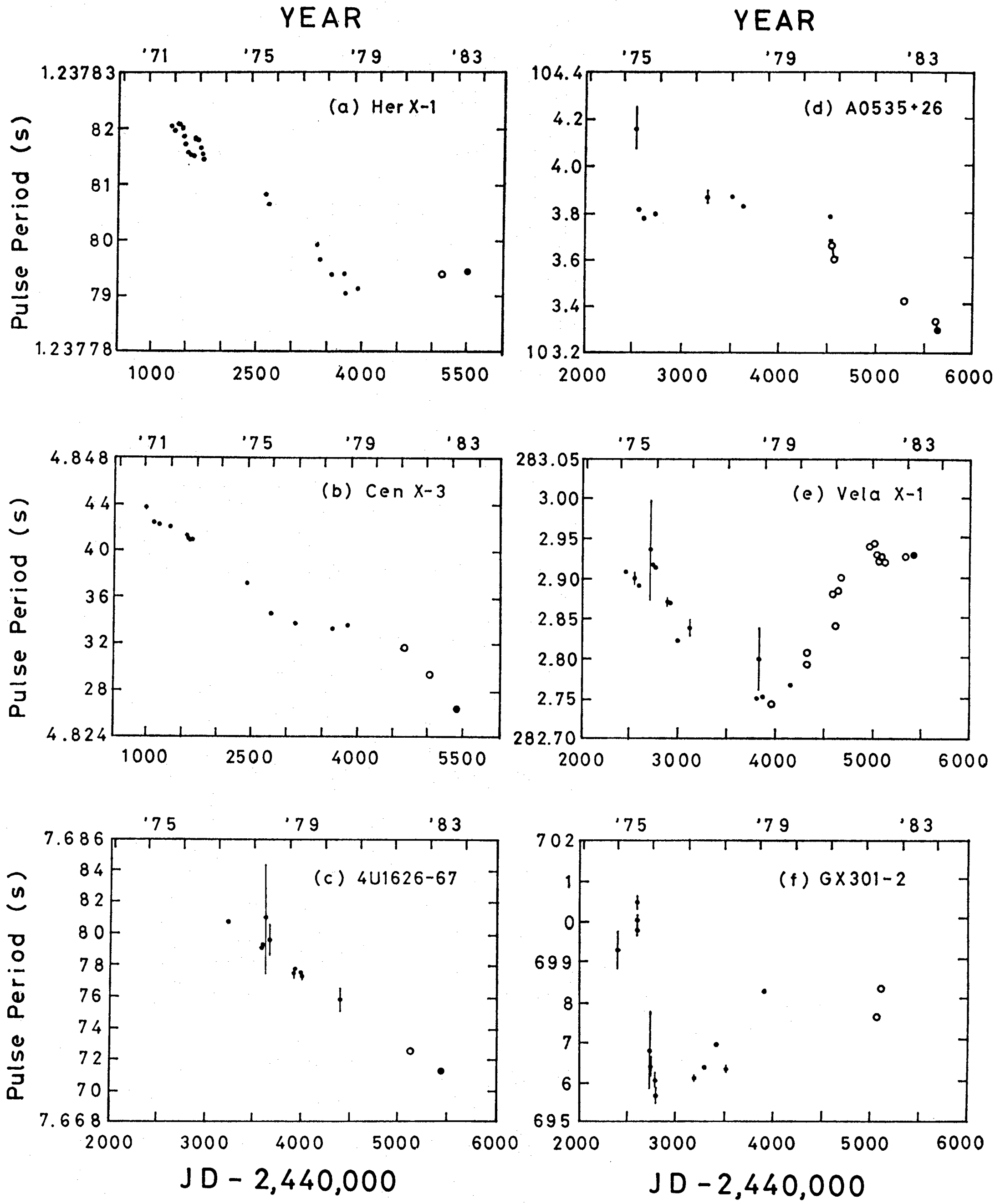

Fig. 1. Pulse-period histories for six X-ray pulsars; (a) Her X-1, (b) Cen X-3, (c) 4U 1626−67, (d) A 0535+26, (e) Vela X-1, and (f) GX 301−2. The data obtained by Hakucho and Tenma are shown by open and filled circles, respectively. Whereas, the previous measurements are referred to Rappaport and Joss (1983), and are plotted by dots. For additional references, see also Deeter et al. (1981) for Her X-1, Kelley et al. (1983), Murakami et al. (1983), and Howe et al. (1983) for Cen X-3, Elsner et al. (1983) for 4U 1626−67, Nagase et al. (1982) for A 0535+26, Nagase et al. (1984) for Vela X-1, and Kelley et al. (1980) for GX 301−2. The vertical bars represent the 1σ uncertainties in the period determinations.

are shown with open and filled circles, respectively, whereas previous data are denoted by heavy dots.

2.1. *Hercules X-1*

Her X-1 was observed with Hakucho from June 13 to 19, 1982. The observation was scheduled according to the turn-on time of the source after the ephemeris tabulated by Crosa and Boynton (1980). However, Her X-1 was already in the high state on June 12.88 (UT), 1982. The X-ray flux was about 0.1 Crab Nebula flux in the energy range 1–22 keV at the start of the observation and gradually decreased to 0.03 Crab Nebula flux on June 16, 1982.

An observation of Her X-1 was also performed with Tenma from May 21 through 31, 1983, well ahead of the expected turn-on time of May 25 based on the prediction by Staubert et al. (1983). The X-ray flux was already ~0.03 Crab Nebula flux in the energy range 2–20 keV at the start of observation on May 21.5 (UT), 1983. The peak flux was 0.06 Crab Nebula flux on May 22.2 (UT), after Her X-1 came out of an eclipse. The X-ray flux gradually decreased and disappeared below the detection limit of ~0.001 Crab Nebula flux of the GSPC counters aboard Tenma after May 28.5 (UT). The pulse modulation was diminished after May 25.2 (UT), and became almost unpulsed after May 26.8, while a finite unmodulated flux of Her X-1 was still as high as 0.02 Crab Nebula flux. Details of the Tenma observation of Her X-1 are described elsewhere by Ohashi et al. (1984).

The pulse periods and their rates of change determined by the combined fit of the above two data sets are listed in table 1. These two pulse periods are significantly displaced from the extrapolation of earlier data with a secular spin-up rate of $\dot{P}/P=(-3.2\pm0.1)\times 10^{-6}\,\mathrm{yr}^{-1}$ (Deeter et al. 1981), as shown in figure 1a. The Hakucho and Tenma results indicate that Her X-1 has started to spin down. It is interesting to note that the EXOSAT observations of Her X-1 between June 28 and July 17, 1983 did not detect a finite X-ray flux during the expected turn-on period (*IAU Circular*, No. 3841, 1983). It is therefore suggested that Her X-1 no longer follows the 35-d turn-on cycle and has entered into an extended low state.

2.2. *Centaurus X-3*

The observations of Cen X-3 were performed on three occasions; (I) March 21–26, 1981, (II) March 16–30, 1982 with Hakucho, and (III) April 4–6, 1983 with Tenma. A transition of X-ray intensity of Cen X-3 from the high state to the low state was detected once on March 27, 1981 during the observation (I) by Murakami et al. (1983). During the observation (II), we detected another transition from the low state to the high state on March 20.6 (UT), 1982. The data obtained during the high state between March 20.6 and 30.7 were used for pulse arrival-time analysis. A transition from the low to high state was also detected with the scanning counters aboard Tenma in March 1983. Cen X-3 was observable with the scanning counters from 11 to 18 in March 1983, prior to the observation with the GSPC counters, and Cen X-3 was found in its low state between March 11.1 and 15.4 and turned onto the high state on March 15.6, 1983.

The result of pulse-timing analysis during the interval (I) was described by Murakami et al. (1983). The data were re-examined together with those from observations (II) and (III). Pulse arrival-time analysis of the combined data sets gives significant rates of period change for the observations (I) and (II), as listed in table 1. We note that the spin-up rates of $\dot{P}/P=(-0.78\pm0.14)\times10^{-4}\,\mathrm{yr}^{-1}$ and $\dot{P}/P=(-9.01\pm0.07)\times10^{-4}\,\mathrm{yr}^{-1}$ measured during the observations (I) and (II) are appreciably different from the secular spin-up rate of $\dot{P}/P=-5.5\times10^{-4}\,\mathrm{yr}^{-1}$ in 1981–1983. The short-term spin-up and spin-down episodes were also obtained by HEAO-1 observations (Howe et al. 1983). The pulse periods measured are shown in figure 1b together with those obtained previously. One can see a large wavy fluctuation of pulse-period variation on the time scale of several years around the average spin-up rate of $\dot{P}/P=-2.7\times10^{-4}\,\mathrm{yr}^{-1}$. This pulse-period change and the short-term variations of pulse period are reminiscent of those of Vela X-1.

Another remarkable feature of Cen X-3 is a change in the orbital period. Eclipse centers of JD 2,445,049.6025 $\pm$ 0.0001 (1σ) and JD 2,445,429.45421 $\pm$ 0.00005 (1σ) were obtained from pulse-timing analysis for the observation intervals (II) and (III), respectively. These epochs of eclipse centers are consistent with an extrapolation of the average rate of $(\dot{P}/P)_{\mathrm{orb}}=-1.8\times10^{-6}\,\mathrm{yr}^{-1}$ derived by Kelley et al. (1983).

2.3. *4U 1626−67*

The X-ray source 4U 1626−67 is the unique X-ray pulsar as it belongs to a low-mass binary system (Middleditch et al. 1981) and exhibits a stable spin-up at a rate of $\dot{P}/P=-2\times10^{-4}\,\mathrm{yr}^{-1}$ (Rappaport et al. 1977; Elsner et al. 1983). The pulsation was measured on July 2–6, 1982 with Hakucho and May 2–6, 1983 with Tenma. The pulse periods determined are $P=7.67271\pm0.00003$ s and $P=7.671350\pm0.000003$ s, respectively, as plotted in figure 1c.

The spin-up rate of this X-ray pulsar is quite stable in contrast to the other X-ray pulsars such as Her X-1, Cen X-3, and Vela X-1. All the pulse periods of 4U 1626−67 obtained are consistent with the average spin-up rate of $\dot{P}/P=(-1.98\pm0.02)\times10^{-4}\,\mathrm{yr}^{-1}$ as seen in figure 1c. The pulse-timing data measured with Tenma in May 1983 give a finite value of spin-up rate of $\dot{P}/P=(-5.3\pm1.6)\times10^{-4}\,\mathrm{yr}^{-1}$. This value is marginally significant but not inconsistent with the secular rate of spin-up within the accuracy of determination.

2.4. *OAO 1657−415*

White and Pravdo (1979) discovered X-ray pulsation at 38.218 ± 0.004 s from OAO 1657−415 (Byrne et al. 1981). About a year later Parmar et al. (1980) obtained a pulse period of 38.019 ± 0.009 s from the Einstein Observatory on August 25, 1979.

We observed the X-ray pulsar OAO 1657−415 for five days from July 18 through July 23, 1983, and obtained a pulse period of $P=37.885\pm0.001$ s. The rate of pulse-period change of $\dot{P}/P=-9.0\times10^{-4}\,\mathrm{yr}^{-1}$ between August 1979 and July 1983 is significantly small compared to that of $\dot{P}/P=-5\times10^{-3}\,\mathrm{yr}^{-1}$ obtained between September 1978 and August 1979. In spite of a relatively long span of observation, we were unable to find any evidence of Doppler delay in the pulse arrival times. The upper limit of $\Delta t=2.0$ s (2σ confidence limit) was obtained for the difference of pulse delay times during the 5.5-d observation, assuming the constant pulse period derived above. Hence this X-ray pulsar is suspected of belonging to a low-mass binary system, although the possibility of a massive binary system with a large orbital period over several tens of days or with a small inclination angle cannot be rejected. Details of the timing analysis will be published separately.

2.5. *A 0535+26*

A 0535+26 is a recurrent transient X-ray pulsar with a Be companion star. An outburst of A 0535+26 was observed with Hakucho from October 2 to November 3, 1980. We found that this transient X-ray pulsar underwent outbursts in accordance with the 111-d period of recurrence. Restrictions on the orbit of the binary system were also investigated by pulse arrival-time analysis during the observation (Nagase et al. 1982).

A small outburst of the X-ray source was observed during November 12 to 20, 1982 with Hakucho. The peak flux in the energy range 1–22 keV was about 0.2 Crab Nebula flux. The apparent pulse period of $P=103.423\pm0.003$ s is appreciably smaller than the period in the previous observation in 1980.

On October 1, 1983, an outburst of A 0535+26 was again detected with Hakucho. The X-ray intensity gradually increased to a maximum of 0.5 Crab Nebula flux in the energy range of 1–22 keV around October 10 and then slowly decreased. The observation was continued by Tenma from October 24 through 26, 1983 and about the 0.05 Crab Nebula flux was detected during the observation period. The apparent pulse period of $P=103.3429\pm0.0007$ s is obtained together with a large $\dot{P}$ and a significant $\ddot{P}$ for the observation period, as shown in table 1. In the case of A 0535+26, it should be noted that the finite $\dot{P}$ and $\ddot{P}$ obtained for observations in 1980 and in 1983 are not necessarily due to changes in the intrinsic pulse period, because the orbital parameters of A 0535+26 are not yet determined and a part of the measured values of $\dot{P}$ and $\ddot{P}$ could be explained by the Doppler effect of the orbital motion.

The three observations with Hakucho and Tenma indicate a secular decrease in the pulse period at an average rate of $\dot{P}/P=-1.2\times10^{-3}\ \mathrm{yr}^{-1}$ in the last three years (see figure 1d), in contrast to the complex spin-up and spin-down behavior before 1980. Both of the outbursts in 1982 and 1983 occurred as expected from the 111-d recurrence (Nagase et al. 1982; Watson et al. 1982). Recent studies of the Vela 5B satellite X-ray data (Priedhorsky and Terrell 1983a) and the optical observation of HDE 245770 in the *V*-band (Guarnieri et al. 1984) have also derived periods of 111.0 ± 0.4 d and 110.8 ± 0.4 d, respectively.

2.6. *Vela X-1*

The X-ray pulsar Vela X-1 has been most intensively monitored with Hakucho. The pulse periods measured for fourteen oribtal cycles from March 1979 to December 1982 were described by Nagase et al. (1984) . Secular spin-down at a rate of $\dot{P}/P=2.7\times10^{-4}\ \mathrm{yr}^{-1}$ was detected during the observation interval between March 1979 and December 1981. After January 1982, the secular spin-down ceased, and the pulse period has stayed at a constant value of $P=282.935\pm0.010$ s as seen in figure 1e. Short-term fluctuations of the pulse period on a time scale of a week were superimposed on the secular trend of the period change (Nagase et al. 1984). The absolute values of the short-term period changes are as large as $\dot{P}/P=4\times10^{-3}\ \mathrm{yr}^{-1}$ with both positive and negative values, which is an order of magnitude larger than the long-term average of the spin-down rate.

The pulse period of $P=282.9306\pm0.0003$ s measured with Tenma in March 1983 confirmed the recent trend toward constant pulse period observed with Hakucho. The fitting of 287 pulse arrival times measured over fifteen days of Tenma observations yields a small but a finite rate of period change of $\dot{P}=(-5.3\pm0.3)\times10^{-9}\ \mathrm{s\ s}^{-1}$, or $\dot{P}/P=(-5.9\pm0.3)\times10^{-4}\ \mathrm{yr}^{-1}$. The orbital elements obtained from the timing analysis based on the Tenma data are consistent with those of the previous works (Rappaport et al. 1980; Nagase et al.

Table 2. Orbital elements of Vela X-1 measured with Tenma in March 1983.[a]

$a_x \sin i$	111.9 ± 0.2 light-s
e	0.091 ± 0.002
ω	$152^\circ.0\pm0^\circ.6$
τ	JD 2,445,410.10$\pm$0.02
P_{orb}	8.9642 d[b]

Notes:

[a] All quoted uncertainties are single parameter 1σ confidence limits.

[b] Orbital period was fixed to a constant value derived from Hakucho data (Nagase et al. 1984).

1984) with a slight improvement in the accuracy of determination as given in table 2.

2.7. 4U 1538−52

The 8.8-min pulsation of the eclipsing X-ray binary 4U 1538−52 was discovered by the experiment on board Ariel-5 (Davison 1977) and OSO-8 (Becker et al. 1977) in August and September 1976. An orbital period of 3.7299±0.0012 d and a pulse period of 528.929±0.040 s were obtained together with a projected semimajor axis of 55.2±4.3 light-s from these observations (Davison et al. 1977).

The X-ray pulsar 4U1538−52 was observed with Tenma during the period from June 28 to July 6, 1983. We obtained a pulse period of $P=529.772\pm0.006$ s assuming a circular orbit, which indicates an increase in the pulse period at a rate of $\dot{P}/P=2.4\times10^{-4}$ yr^{-1} for the seven years span. We also determined the eclipse center at JD 2,445,514.18±0.05 d, which in combination with the Ariel-5 and OSO-8 results as well as the optical information by Crampton et al. (1978), yields a more accurate value of the orbital period of $P_{\mathrm{orb}}=3.72821\pm0.00006$ d. A value for the projected semimajor axis of 56.1±1.5 light-s is also obtained from the pulse-timing analysis.

The binary system of 4U 1538−52 is similar to that of Cen X-3. However, the former shows an increase in the pulse period at a rate of $\dot{P}/P=2.4\times10^{-4}$ yr^{-1} for the long interval of seven years, on the contrary to the average spin-up of Cen X-3. This increase in the pulse period may result from the accumulation of a short-term pulse-period change of altering sign as observed by the wavy period fluctuation of Cen X-3. In fact, the pulse period of 4U 1538−52 changed at a rate of $\dot{P}/P=(1.2\pm0.4)\times10^{-2}$ yr^{-1} during the observation.

2.8. GX 301−2

The transient X-ray pulsar GX 301−2 is a binary system with a B1.5 Ia star and a highly eccentric orbit. Two consecutive outbursts were detected with Hakucho on April 1–24 and May 15–20, 1982 in accordance with the 41.5-d orbital period given by Watson et al. (1982). We derived an orbital period $P_{\mathrm{orb}}=41.524\pm0.006$ d from the timing analysis of the two data sets in conjunction with earlier results (Kelley et al. 1980; White and Swank 1984). This is in good agreement with 41.52±0.02 d reported by Priedhorsky and Terrell (1983b).

The pulse periods measured in these two time intervals are shown in figure 1f. It may be of some importance that a significant spin-down occurred between two consecutive flares. The history of the pulse period of GX 301−2 is complex as seen in the figure; a secular trend of spin-up as well as spin-down on a time scale of a few years is somewhat similar to that of Vela X-1. The joint fit of the two data sets suggests the possible existence of a short-term variation of the pulse period at a rate of $\dot{P}/P=(1.4\pm0.4)\times10^{-2}$ yr^{-1} during the observation on April 1–24, 1982.

The pulse profile of this X-ray source is highly variable. In particular, the pulse fraction changes drastically so that the pulse component sometimes disappears (Mitani et al. 1984; White and Swank 1984).

3. Discussion

Before the Hakucho and Tenma observations, Her X-1 and Cen X-3 had been known as disk-fed X-ray pulsars exhibiting a steady long-term decrease of pulse period, although finite variations of the pulse period on short time scales were superposed on the secular spin-up trend [Giacconi (1974); see also Joss et al. (1977) for Her X-1, Fabbiano and

Schreier (1977) and Howe et al. (1983) for Cen X-3]. The present results indicate that changes in the secular trend of pulse period are common features both for the wind-fed pulsars, such as Vela X-1, GX 301−2, and A 0535+26, and for the disk-fed pulsars, such as Cen X-3 and Her X-1. Stable spin-up is observed only for a few X-ray pulsars. As seen in figure 1c, 4U 1626−67 exhibits stable spin-up over six years from 1977 to 1983. GX 1+4 and SMC X-1 also show similar properties over ten years [e.g., see Rappaport and Joss (1983)].

Her X-1, which is considered to be a typical disk-fed pulsar, showed a remarkable change in the long-term behavior of the pulse period. The spin-down observed in May 1983 is in sharp contrast to the general spin-up at a rate of $\dot{P}/P=-3\times10^{-6}\ \mathrm{yr}^{-1}$ with a small fluctuation of $\Delta P=(2\text{–}5)\times10^{-6}$ s from orbit to orbit. The pulse period in May 1983 is larger by $\Delta P=2\times10^{-5}$ s than that extrapolated with the average spin-up rate. The value of period increase is significantly larger than that for the short-term variation observed in 1972 (see figure 1a). It is interesting to ask if the unusual phenomena observed in 1983, such as the X-ray pulsar entering into an extended low state (*IAU Circular*, No. 3841, 1983) and the disappearance of X-ray pulses (Ohashi et al. 1984), are related to the spin-down of Her X-1.

Cen X-3, another typical disk-fed pulsar, shows a wavy fluctuation of the pulse period around the average trend of spin-up. No conspicuous phenomena have yet been observed in association with the period change.

A correlation between pulse-period change and the X-ray luminosity has been explained in terms of angular momentum transfer from accreting matter (Rappaport and Joss 1977; Ghosh and Lamb 1979). However, the correlation has not yet been established empirically even for such pulsars as Her X-1 and Cen X-3. Correlation between pulse-period change and the X-ray luminosity is suspected only for the X-ray pulsar A 0535+26, which has shown high spin-up rates during large outbursts. It is therefore likely that complex processes take part in the pulse-period change; that is, the accretion rate is not the sole controlling factor.

Among the six X-ray pulsars shown in figure 1, Vela X-1, A 0535+26, and GX 301−2 exhibit more complex behavior of pulse-period changes. These X-ray pulsars are considered to be wind-fed, and they have pulse periods longer than 100 s. The mechanism of torque reversal in such wind-fed X-ray pulsars has been discussed by several authors and reviewed by Henrichs (1983).

Vela X-1 is considered to be a typical wind-fed pulsar. It shows both spin-up and spin-down on a time scale of a few years as seen in figure 1e. Extensive observations with Hakucho revealed short-term fluctuations of pulse period on a time scale of several days (Nagase 1981; Nagase et al. 1984). In figure 2 we show the number distribution of the rate of short-term period change obtained by Molteni et al. (1982), by Bautz et al. (1983), and by Nagase et al. (1984).

The distribution can be represented by a Gaussian one with an average rate of period change,

$$\langle\dot{P}\rangle=(10.8\pm4.4)\times10^{-9}=0.0083\pm0.0034\ \mathrm{s\ orbit}^{-1},$$

and standard deviation,

$$\sigma_{\dot{P}}=(15.8\pm4.2)\times10^{-9}=0.0122\pm0.0033\ \mathrm{s\ orbit}^{-1}.$$

The positive value of average rate of period change follows because the data were sampled during the general spin-down phase between 1979 and 1983. This suggests that the long-term variation of pulse period results from the accumulation of short-term fluctuations

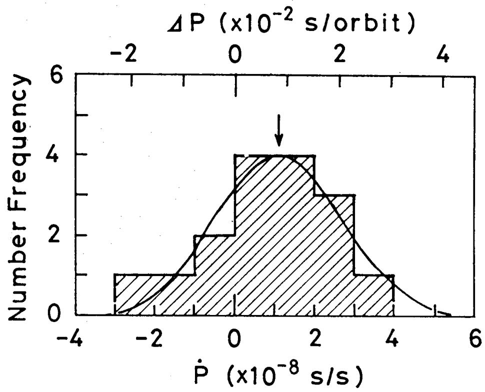

Fig. 2. Number frequency distribution of the rates of change of the pulse period in Vela X-1 obtained during respective observations. Data are taken from Molteni et al. (1982), Bautz et al. (1983), and Nagase et al. (1984). The solid curve represent the best-fit Gaussian distribution (see text).

with both positive and negative values. In fact, the observed period increase of 0.2 s during three years from 1979 to 1982 (about 100 orbital cycles) is roughly equal to an accumulation of random walks with a step of $\sigma_P \sim 0.01$ s orbit^{-1}.

It is interesting to obtain distributions of short-term period change for A 0535+26 and GX 301−2 to see if the same holds for other wind-fed pulsars. The finite value of short-term period change in GX 301−2 derived in the present fitting suggests that the same accumulation mechanism of short-term fluctuations could presumably be responsible for the secular change of the pulse period of GX 301−2. It would also be useful to look for intrinsic period changes in Vela X-1 on a time scale shorter than the orbital period. Recently, van der Klis and Bonnet-Bidaud (1984) have attempted to look for such shorter time-scale variations of the pulse period of Vela X-1 using the COS-B satellite X-ray data. The present observations of Cen X-3 and Her X-1 suggest that these X-ray pulsars also show both short-term variations and secular changes of pulse period, and the rates of short-term period change of the disk-fed pulsars are comparable to those of the wind-fed pulsars.

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