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OBSERVATION OF AN OUTBURST OF THE TRANSIENT X-RAY PULSAR A0535+26 IN 1980

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ABSTRACT

An outburst of the recurrent X-ray transient A0535+26 was detected on 1980 October 2, and the source was continually observed by *z*-axis detectors on board the *Hakucho* satellite for 25 days from October 9 to November 3. The observed X-ray light curve showed a maximum of ~1.5 times the Crab Nebula flux on October 10 and monotonically declined during the course of the observation. The present outburst seems to have occurred on time according to the regular ~110 day recurrence of outbursts. Analysis of the pulse arrival time gives a lower limit on the orbital period of 40 days, whereas the upper limit is ~120 days considering the mass function derived from optical data. The orbital eccentricity of 0.2–0.4 is required for the above range of orbital period. The pulse period data obtained during the outburst favor an intrinsic decrease of the pulse period at a rate of $-\dot{P}/P \approx 2 \times 10^{-10}\ \mathrm{s}^{-1}$ with a decreasing rate roughly proportional to X-ray luminosity. A consistent picture is drawn with an eccentric orbit of a ~110 day period, whereby recurrent outbursts occur near the periastron passages.

Subject headings: stars: pulsation — X-rays: binaries

I. INTRODUCTION

The recurrent transient X-ray source A0535+26 was discovered with the *Ariel 5* satellite in 1975 April by Rosenberg *et al.* (1975). They also reported pulsations with a period of 104 s. Light curves of the outbursts and the energy spectra in the rising and declining phases were measured (Coe *et al.* 1975; Ricketts *et al.* 1975; Kaluzienski *et al.* 1975; Maraschi *et al.* 1976). Complex, energy dependent pulse profiles in the low-energy range, similar to those of Vela X-1, were reported by Bradt *et al.* (1976), whereas the pulse profiles in the high-energy range exhibit a simple form with a flat top and a narrow dip (Ricker *et al.* 1976). The recurrence of outbursts and the change of the pulsation period were followed by the *SAS 3* satellite until March 1978 (Rappaport *et al.* 1976; Li *et al.* 1979).

The optical companion of A0535+26 was identified with a ninth magnitude Be star HDE 245770 (Stier and Liller 1976), at a distance estimated to be 1.3–1.8 kpc (Hutchings *et al.* 1978; Giangrande *et al.* 1980). No optical pulsation was observed during an X-ray outburst with an upper limit of 0.0002 mag (Margon *et al.* 1977). An infrared excess with the spectrum $\nu^{-0.6}$ in J, H, K, and L bands was reported by Persi *et al.* (1979). They explained the excess in terms of thermal free-free emission from an ionized gaseous envelope around the companion star.

In spite of much effort to obtain orbital parameters of the systems, no reliable binary period has yet been obtained. Hutchings *et al.* (1978) suggested possible periods of about 28, 48, or 94 days, from several optical data of radial velocities and line intensities as well as X-ray data. Li *et al.* (1979) obtained four possible orbital periods in the range 30–55 days from the X-ray pulse timing analysis, combining the data observed in 1975 June, 1975 November, and 1978 April under the assumption of a circular orbit.

Further X-ray observations of A0535+26 were made during its outburst in 1980 October with the *Hakucho* satellite. Since X-ray emission was detected over 25 days, the orbital parameters were obtained with stronger restriction than in earlier works; the orbital period was

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derived from the X-ray timing analysis to be longer than 40 days, and its upper limit was restricted by the mass function to be 120 days. It was also suggested (Hayakawa 1981) that outbursts occurred near the periastron passage with an orbital period of about 110 days. In the present paper we give a full account of the X-ray timing analysis that led to these conclusions.

In the pulse arrival time analysis a question had been raised as to whether an intrinsic pulse period change exists or not (Li *et al.* 1979). If a long pulse period observed on 1980 September 25 (Hameury *et al.* 1981) is taken into account, an intrinsic decrease in the pulse period during outbursts is likely to exist. This favors a longer orbital period within the wide period range 40–120 days derived without the assumption of an intrinsic pulse period change.

In § II the X-ray observation in 1980 October is described. The pulse arrival time analysis without intrinsic period change is discussed in § III. Indication of the intrinsic pulse period change is presented in § IV along with its possible mechanism. The recurrence period of outburst is suggested in § V. The conclusions are summarized in § 6.

II. OBSERVATION

An outburst of the recurrent transient X-ray pulsar A0535+26 was detected with the y-axis scanning detectors on board the *Hakucho* satellite on 1980 October 2. Pointed observation with the z-axis narrow field-of-view detectors was performed from 1980 October 9 through November 3, until the X-ray flux of A0535+26 decreased below the detection limit of the z-axis detectors. The data from the detectors with a fine modulation collimator (FMC-1) and with a honeycomb tube collimator (FMC-2) were used in the present analysis. Details of these detectors are described elsewhere (Kondo *et al.* 1981).

The observation was carried out in two energy bands, 1–9 keV and 9–22 keV. The X-ray intensities in these energy bands reached the maximum on 1980 October 10 (JD 2,444,522) and then decreased gradually during the course of observation as shown in Figure 1. The peak intensity was about 1.5 times the Crab Nebula flux in the energy range 1–22 keV. The averaged flux over each pulse was found to vary irregularly by 20%–50% from pulse to pulse.

The hardness ratio, which is the ratio of the X-ray flux in 9–22 keV to that in 1–9 keV, is also shown in the upper diagram of Figure 1. The hardness ratio for each satellite orbit of ~100 minutes remained constant within statistical errors in spite of the erratic variation of X-ray intensity from pulse to pulse. However, a long-term trend of decrease in the hardness ratio is noted in the declining phase of the light curve. Coe *et al.* (1975) and Ricketts *et al.* (1975) also reported such a softening in both the rising and the declining phases of the outburst in 1975 April. It is worth mentioning that the bright X-ray transient A0620−00 (Nova Monocerotis 1975) also exhibited similar spectral softening (Ricketts, Pounds, and Turner 1975; Matilsky *et al.* 1976), whereas there are some transient X-ray sources, such as Cen X-4 (Matsuoka *et al.* 1980), which do not show significant changes in spectrum during the course of outbursts.

The apparent pulse period averaged over a day was obtained directly by folding the data modulo trial periods of 103–104 s. In the folding procedure, the χ^2-maximum search method was used for the combined data observed in several satellite orbits within a day, assuming a constant source intensity. This method gives a unique value of the period with a statistical uncertainty of 0.0015–0.005 s for each day. The time variation of the pulse period is shown in Figure 2 after correcting for the heliocentric motion of the earth.

The observed pulse period during the present outburst decreases as a function of time with a diminishing rate of change, and in the later part of the observation the period seems to stay constant. The pulse periods of 103.67 s to 103.61 s observed during this outburst are significantly smaller than the period of 103.84 s in 1978 April by Li *et al.* (1979). The history of period change from 1975 to 1980 is shown in Figure 3. The apparent rate of spin-up between 1977 and 1980 is $-\dot{P}/\dot{P} \approx 0.8 \times 10^{-3}$ yr^{-1} as seen in the figure.

III. PULSE ARRIVAL TIME ANALYSIS

We obtained a total of 188 epochs of pulse arrival time during the span of observation from 1980 October 8.96 to November 3.54 (UT). We folded the uninterrupted data for each satellite orbit to obtain a statistically smooth average pulse light curve from which the epoch of arrival time could be accurately determined. A typical uncertainty for the determination of epochs was 1.5 s at the beginning of the observation and increased up to 5 toward the end of the observation due to the degrading signal-to-noise ratio. All epochs are converted to the heliocentric pulse arrival times by correcting for the orbital motion of the earth.

At first the observed data of pulse arrival times were fitted by a kth order polynomial of the form

$$t_n = t_0 + P_0 n + a_1 n^2 + \cdots + a_{k-1} n^k, \qquad (1)$$

where t_n is the arrival time of the nth pulse, P_0 is an intrinsic pulse period at epoch t_0, and coefficients a_j represent the jth order derivatives of intrinsic pulse period of the form,

$$a_j = \frac{P_0^j}{(j+1)!}(d/dt)^j P, \quad j = 1,2,\ldots,k-1. \qquad (2)$$

The fitting with the fourth-order polynomial is found to be quite satisfactory with a reduced χ^2 minimum of 0.42

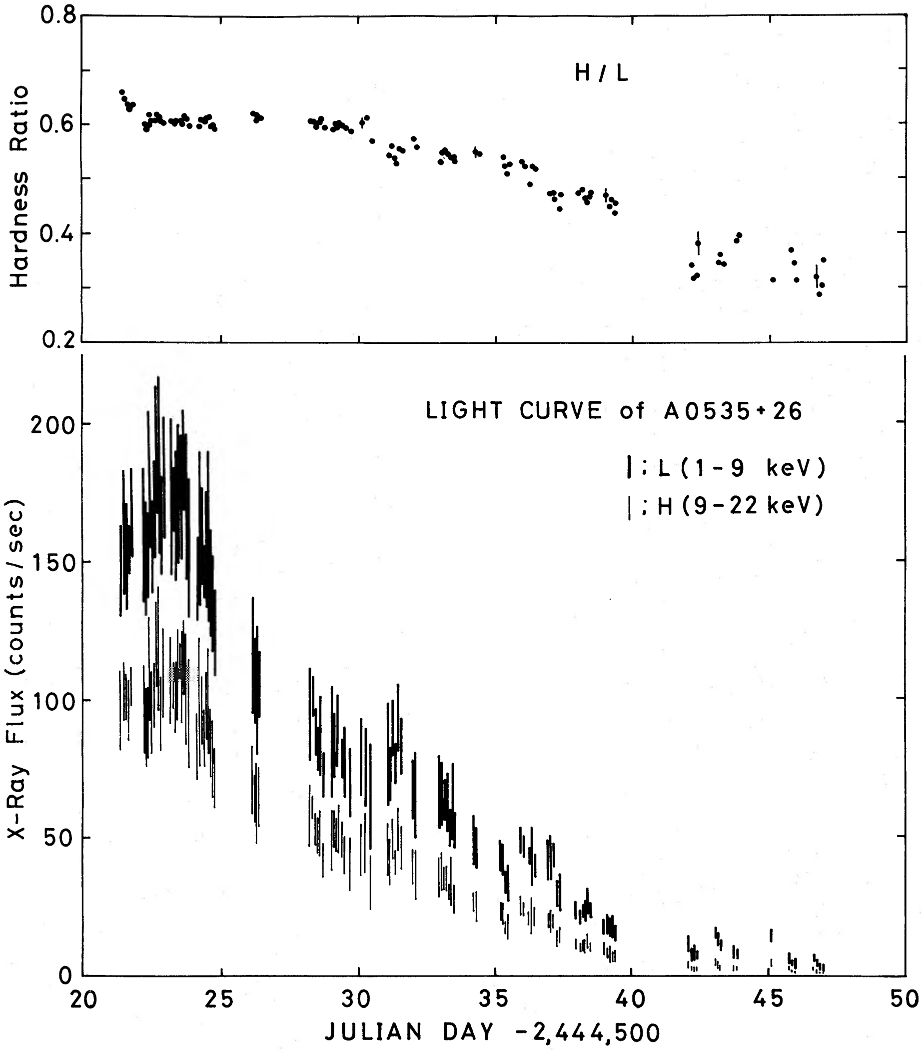

FIG. 1.—The light curve of the outburst in 1980 October of the transient X-ray source A0535+26. The X-ray fluxes averaged over a pulse at 1–9 keV (*dark bars*) and 9-22 keV (*light bars*) are shown together with their ratios. The length of bar represents the variability of the X-ray flux from pulse to pulse within an orbit of satellite.

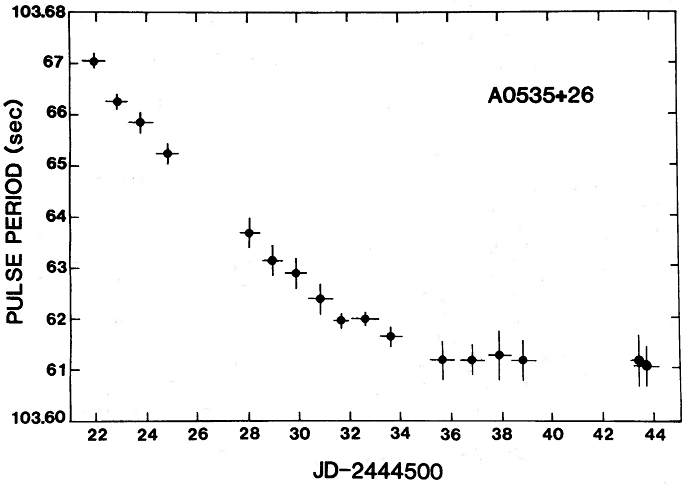

FIG. 2.—The change of apparent pulse period of A0535+26 derived from the observation in 1980 October.

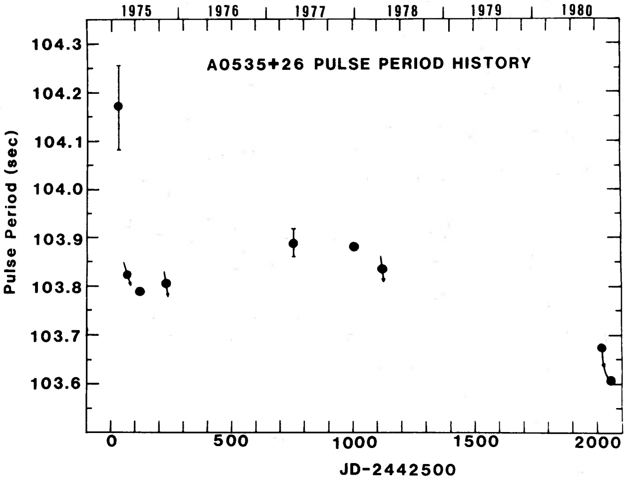

FIG. 3.—The history of the period change in A0535+26. The data points other than in 1980 October are taken from Li *et al.* 1979.

together with the following set of best fit parameters,

$$P_0 = 103.6471 \pm 0.0002 \text{ s}, \quad \text{at } t_0 = \text{JD } 2{,}444{,}521.4652,$$

$$\dot{P} = (-8.428 \pm 0.045) \times 10^{-8},$$

$$\ddot{P} = (+6.36 \pm 0.10) \times 10^{-14} \text{ s}^{-1},$$

$$\dddot{P} = (-1.51 \pm 0.12) \times 10^{-20} \text{ s}^{-2}. \qquad (3)$$

An unusually small value of the reduced χ^2-minimum of 0.42 is suspected to be due to an overestimate of the uncertainties for the determination of epochs. The fitting with the second-order polynomial does not give an allowable χ^2. In the case of the third-order polynomial, the minimum reduced χ^2 is greater by a factor of 1.4 than that in the case of the fourth order. The fifth- or higher order terms do not improve the fitting. The delays of the pulse arrival times are shown in Figure 4 together with the best fit third- and fourth-order polynomial delay curves.

From the observed result, it is difficult to conclude whether the observed change in the pulse period is due to orbital motion, is intrinsic to the X-ray source A0535+26, or both. In the following analysis we first derive restrictions on the orbital parameters under the assumption that the observed period change in the present observation is due exclusively to the orbital motion of the X-ray star.

We fit the data with a function of the form that includes the effect of eccentricity,

$$t_n = t_0 + P_0 n + a_x \sin i F(e, \omega, \tau, \theta), \qquad (4)$$

where $a_x \sin i$ is the projected semimajor axis of the orbit of the X-ray star. The function F describes the pulse arrival time delays due to the orbital motion, in which e, ω, τ, and θ represent the eccentricity, the longitude of periastron, the time of periastron passage, and the mean anomaly, respectively. The mean anomaly is related to the orbital period P_{orb} as $\theta = 2\pi(t-\tau)/P_{\text{orb}}$.

Among seven free parameters t_0, P_0, $a_x \sin i$, e, ω, τ, and P_{orb}, we first search for acceptable sets of parameters in the $e-\omega$ plane for each assumed orbital period. We find acceptable sets with the reduced χ^2_{min} of 0.40–0.41 for orbits of $P_{\text{orb}} \geq 45$ days. This χ^2_{min} values are comparable to that found for the fitting with the fourth-order polynomial of Equation (1). Examples of the projections of acceptable regions in the e-ω plane are shown in Figures 5a and 5b, in which the 90% (χ^2_{min}+ 4.61, d.o.f. = 180) and 99% (χ^2_{min} + 9.20) confidence con-

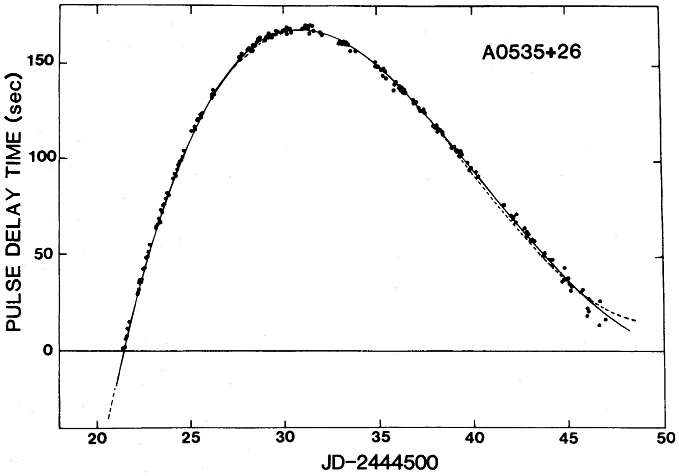

FIG. 4.—The modulation of the pulse arrival times of A0535+26 observed in 1980 October. The solid and dashed lines represent the best fit 4th and 3rd orders of polynomial given by eq. (1), respectively.

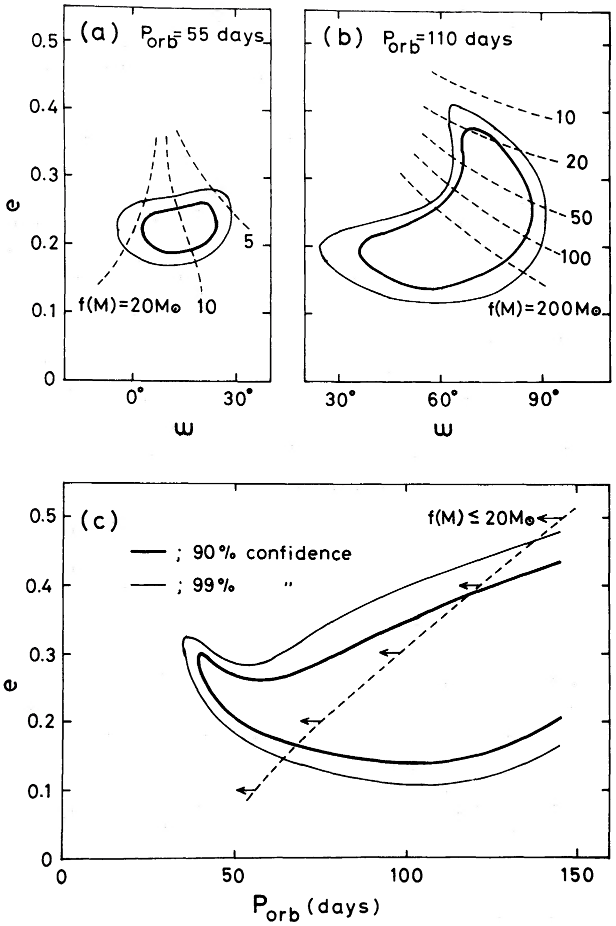

FIG. 5.—The acceptable regions of orbital parameters of A0535+26. The 90% (*thick line*) and the 99% (*thin line*) confidence contours in the e-ω plane are shown for the fixed orbital period of (a) 55 days and (b) 110 days. The dashed lines show the equal mass function levels. The same contours in the $e - P_{\rm orb}$ plane are shown in (c). The allowable region for $f(M) \leq 20\ M_\odot$ is shown by the dashed line with arrows.

tours for two parameters are shown by the thick and thin lines, respectively. The resulting contours projected on the $e - P_{\rm orb}$ plane are shown in Figure 5c. From this result, the orbits of periods less than 40 days are rejected with 90% confidence, whereas the upper limit of the orbital period is undetermined.

However, we can set an upper limit on the orbital period by a consideration of the mass function estimated from optical data. The dashed lines in Figures 5a and 5b represent equal mass function lines derived for the best fit projected semimajor axis $a_x \sin i$. The mass of the optical companion is estimated to be 5–20 $M_\odot$ (Hutchings *et al.* 1978), which constrains the mass function to

$$f(M) = \frac{M_\star}{(1+q)^2} \sin^3 i \leq 20\ M_\odot, \qquad (5)$$

where $M_\star$ is the mass of the companion star and q is the mass ratio of the X-ray star to the companion star. This upper limit of the mass function defines the allowable region on the $e - P_{\rm orb}$ plane as shown by the dashed line in Figure 5c. This gives an upper limit for $P_{\rm orb}$ of about 120 days. The figure shows that a longer orbital period requires a higher eccentricity.

IV. INTRINSIC PULSE PERIOD CHANGE

We have thus far assumed that the time variation of pulse arrival time is due entirely to the orbital motion, neglecting the intrinsic change in pulse period. We have thus obtained a lower limit of 40 days for the orbital period with the 90% confidence level, which rules out possible shorter periods of about 28 days and 30 days as suggested by Hutchings *et al.* (1978) and by Li *et al.* (1979), respectively.

The above conclusions would have to be reserved, if there were an intrinsic increase of pulse period, since this would require a greater rate of period decrease due to the orbital motion, thus requiring a shorter period. However, the pulse period increase of intrinsic origin is considered to be unlikely because of the following reasons. No increase of pulse period has ever been observed during outbursts, and a slight net increase from late 1975 to early 1977 gives an average increase rate far smaller than the decrease rate during outbursts, as seen from Figure 3. This argument might be regarded as weak, in view of the fact that Vela X-1 has shown intrinsic period changes of alternating signs (Nagase 1981; Nagase *et al.* 1982).

A strong argument is provided by the large pulse period of 103.79 s observed on 1980 September 25 by Hameury *et al.* (1981). This results in that a decrease of the pulse period continued over 30 days and did not turn into an increase even after 37 days. This not only strengthens the conclusion of excluding the orbital period shorter than 40 days but also favors a period considerably longer than the lower limit.

The following discussion suggests the existence of an intrinsic pulse period decrease rather than increase. If the decrease of pulse period from 103.79 s to 103.61 s over 30 days were due entirely to the orbital motion, the X-ray source would have to move toward the observer with a velocity of several hundred km s^{-1} and an orbital period longer than 80 days and $a_x \sin i \gtrsim 800$ lt-sec, requiring $f(M) \gtrsim 150\ M_\odot$. This greatly exceeds the mass expected for the companion star. If an intrinsic decrease of pulse period exists, only a part of the period decrease is attributed to the orbital motion, which requires a smaller orbital velocity and therefore a shorter semimajor axis. The semimajor axis of about 500 lt-sec suffices to reduce the mass below the permitted upper limit of 20 $M_\odot$ for $P_{\rm orb} \gtrsim 80$ days. The orbital period of about 100 days and the rate of intrinsic period change of about $\dot{P}/P \approx -2 \times 10^{-10}$ s^{-1} are one of the possible sets to explain the observed period change.

The intrinsic period change is probably caused by the accretion torque. In the case of wind-fed accretion, the accretion torque is given by (Shapiro and Lightman 1976)

$$N = \tfrac{1}{2} v_x (r_a^2/r) \dot{M}, \tag{6}$$

where v_x and r are the orbital velocity and the stellar separation, respectively, and r_a is the accretion radius given by

$$r_a = \xi 2GM_x/v_0^2, \tag{7}$$

where ξ is a numerical coefficient of order unity, G is the gravitational constant, M_x is the X-ray star mass, and v_0 is the relative velocity of the stellar wind with respect to the X-ray star. Since v_x is much smaller than the wind velocity, v_0 is practically equal to the wind velocity. If this is 500 km s^{-1}, we have $r_a \approx 10^{11} \xi (M_x/M_\odot)$ cm. Since $v_x/r \approx 10^{-6}$ s^{-1}, we obtain

$$-\frac{\dot{P}}{P} = \frac{PN}{2\pi I} \approx 1 \times 10^{-10} \frac{\dot{M}_{17}}{I_{44}} \text{ s}^{-1}, \tag{8}$$

where I_{44} is the moment of inertia of the neutron star crust in 10^{44} g cm^2 and $\dot{M}_{17}$ is the accretion rate in 10^{17} g s^{-1}. As the X-ray luminosity is about 10^{37} ergs s^{-1} for the assumed distance of 1.5 kpc, which corresponds to $\dot{M}_{17} \approx 1$, the accretion torque can explain the intrinsic period change.

The above consideration supports an intrinsic period change caused by the wind-fed accretion torque. The spin rate of the crust thus increased during an outburst decreases by the friction with the inner core in the absence of accretion between outbursts. The extended time base combining our observation with the previous *SAS 3* observations (Rappaport *et al.* 1976; Li *et al.* 1979) may enable us to carry out a more detailed analysis of orbital fitting including the intrinsic variation of pulse period. Results from a detailed analysis will be given in a separate paper.

V. RECURRENCE PERIOD OF OUTBURST

The time of periastron passage derived from the present fitting lies between JD 2,444,510 and JD 2,444,525 for the acceptable sets of P_{orb} and e shown in Figure 5*c*. This indicates that the turn-on (JD 2,444,502) and the peak (JD 2,444,523) of the present outburst occurred near the periastron passage.

In Table 1 we summarize the observed epochs, durations, and X-ray intensities in units of the Crab Nebula flux for all the outbursts reported since the discovery of 1975 April by *Ariel 5*, together with the cycle number and the orbital phase at the flare-up folded modulo 111 days from the temporal origin of epoch JD 2,442,500, which is arbitrarily taken as phase 0. The result is consistent with a 111 day periodicity of the recurrent outbursts. For the employed orbital period, all outbursts listed in Table 1 seem to have occurred near the periastron passage as in the 1980 October outburst.

Recently an unusual optical activity of HDE 245770/A0535+26 on 1981 November 19 has been announced by Guarnieri (1981). After this announcement, we have performed the observation of A0535+26 by the *y*-axis scanning detectors on board the *Hakucho* satellite during the period from 1981 December 11–18 and from 1981 December 23–26 and have detected a short-period outburst of the source with a duration of ~3.5 hours and with a flux of ~0.2 times that of the Crab Nebula at 1400–1730 (UT) on 1981 December 13. No positive flux above the detection limit (~0.1 Crab unit flux) has been detected in the period other than the above. This short-period outburst coincides with the phase of ~0.1 of 22 cycles after the 1975 April event as shown in Table 1.

The earliest outburst observed in 1970 December by *Uhuru* (Forman, Jones, and Tananbaum 1976) is estimated to have occurred also at the phase ~0.1 of 15 cycles before the 1975 April event, although the phase value is not too accurate because the light curve of the outburst was not reported. This suggests that the recurrence of outbursts correlates with the orbital motion of the X-ray source. We note here that for the long-duration, high-luminosity outburst in 1975 April–June, the turn-on phase is appreciably delayed in comparison with other short duration outbursts.

Such an outburst or enhancement of the X-ray luminosity at a time near the periastron passage may be a common property of binary X-ray sources with highly eccentric orbits. The intensity of the X-ray pulsar GX 301−2, the eccentricity of which is estimated to be 0.44, occasionally shows enhancements near the periastron passages (White, Mason, and Sanford 1978; Kelley, Rappaport, and Petre 1980). Another transient X-ray pulsar 4U 0115+63 with a highly elliptical orbit with $e = 0.34$ (Rappaport *et al.* 1978) also shows a similar feature. The peak of the X-ray light curve of the source in a flarelike increase in 1978 January (Rose *et al.* 1979) occurred approximately in coincidence with the periastron passage. The repetitive outbursts with a period of ~190 days of the X-ray pulsar 2S 1145−619 was discovered by the *Ariel 5* SSI observation over 4 yr from 1974 November to 1978 May (Watson, Warwick, and Ricketts 1981). Some other transient X-ray sources, such as 4U 1630−47 (Jones *et al.* 1976), Aql X-1 (Kaluzinski *et al.* 1977; Koyama *et al.* 1981) and the Norma transient 4U 1608−52 (Fabbiano *et al.* 1978; Murakami *et al.* 1980) are also known to undergo quasi-periodic outbursts.

In § III we have obtained an eccentricity of 0.2–0.4 of A0535+26 from the pulse arrival time analysis. A large

TABLE 1

HISTORY OF OUTBURSTS OF THE TRANSIENT X-RAY SOURCE A0535+26

OBSERVATION	DURATION OF OUTBURST[a] Turn-on	Peak	Turn-off	X-RAY FLUX (Crab units)	CYCLE[b] NO.	PHASE[b]	REFERENCES
1975, *Ariel 5, SAS 3*	Apr 21	May 1	June 8	~3 at peak	0	0.21–0.64	1, 2, 3, 4
1975 *Ariel 5, SAS 3*	...	Jul 20[c]	Aug 15	~0.3 at Jul 20	1	· · · –0.25	5, 6
1975, *Ariel 5, SAS 3*	Nov 2	Nov 10	Nov 25	~0.3 at peak	2	−0.04–0.17	5, 7
1977, *SAS 3*	May 20	...[d]	May 24	~0.5 at May 21	7	0.06–0.16	6, 8
1977, *SAS 3*	Dec 20.5	Dec 23.5[e]	...	~0.5 at Dec 23	9	0.05– · · ·	9
1978, *SAS 3*	Apr 10	...	Apr 26	~0.5 at Apr 12.5	10	−0.01–0.13	6, 10
1978, *Ariel 5*	Aug 2 ~ 5	...	Aug 17[f]	~0.4 at Aug 6	11	0.02– · · ·	11
1979, *Ariel 5*	Mar 15	Mar 18[e]	...	~0.25 at Mar 18	13	0.03– · · ·	12
1980, *Hakucho*	Sep 25	Oct 1–10	Nov 3	~1.5 at peak	18	0.02–0.48	13, 14
1981, *Hakucho*	Dec 13[g]	...	...	~0.2 at Dec 13	22	0.09	14

[a] Uncertainty of a few days.

[b] Folded modulo 111 days from the temporal origin of epoch JD 2,442,500.

[c] Observation only in declining phase.

[d] Fluctuating short period outburst.

[e] Observation only in rising phase.

[f] Yet detectable during the declining phase.

[g] Short period outburst.

REFERENCES.—(1) Rosenberg *et al.* 1975. (2) Coe *et al.* 1975. (3) Ricketts *et al.* 1975. (4) Kaluzienski *et al.* 1975. (5) Pounds 1976. (6) Li *et al.* 1979. (7) Rappaport *et al.* 1976. (8) *SAS 3* (*IAU Circ.*, *3073*). (9) Chartres and Li 1977. (10) Clark and Chartres 1978. (11) Kaluzienski and Holt 1978. (12) Sims and Fraser 1979. (13) Hameury *et al.* 1981. (14) This work.

eccentricity was also suggested by Hutchings *et al.* (1978), who derived an eccentricity of 0.5–0.6 from the optical radial velocity curves. Periodic occurrence of outbursts may be caused by the enhancement of mass accretion near the periastron passage in a highly eccentric orbit (Avni, Fabian, and Pringle 1976). Okuda and Sakashita (1977) proposed a model, assuming a high eccentricity $e \approx 0.9$, that the accretion rate of matter fed by the stellar wind from the optical companion is modulated by the distance of stellar separation which varies with the phase of eccentric motion. The mass accretion rate is given by

$$\dot{M} = \pi r_a^2 \rho v_w \propto \rho v_w^{-3}, \qquad (9)$$

where r_a is given in equation (7). The density of stellar wind, ρ, varies with a full amplitude proportional to the ratio $(1+e)^2/(1-e)^2$ if $\rho \propto r^{-2}$. For the maximum permitted value of $e = 0.4$, this gives 5.5, not large enough to explain the ratio of outburst intensity to the nonenhanced intensity. The wind velocity v_w may increase with the distance from the companion star, as is known for the solar wind. An increase in v_w by a factor of 2 at apastron with respect to v_w at periastron may be possible and could account for the outburst if combined with the density variation.

The recurrence of outburst and the variability of enhancement may also be accounted for in terms of a wind pattern which is not uniform in the azimuthal direction. It is interesting to note that most of the recurrent X-ray pulsars are accompanied by Be stars (Rappaport and van den Heuvel 1981) which are supposed to form disks of stellar wind perpendicular to their rotation axes. If the orbit of the X-ray star is inclined with respect to the disk and intersects therewith near the periastron, the accretion rate increases when the X-ray star hits the disk and gradually decreases as it moves away from the periastron until it leaves the disk. The passage of the disk near the apastron may be associated with an unappreciable accretion rate because of too small a value of ρv_w^{-3}. A jitter of outburst epoch and the variabilities of outburst duration and intensity may be due to fluctuations in the density and velocity distributions of wind.

A difficulty in the above model is the durations of outbursts which sometimes last the orbital phase ~0.5.

Large fluctuations in the duration and intensity of bursts require an inhomogeneous wind pattern which considerably fluctuates in time.

VI. CONCLUSION

An outburst of the recurrent transient X-ray pulsar A0535+26 was detected with the *Hakucho* satellite on 1980 October 2. The light curve in the declining phase was obtained from 1980 October 9 through November 3. The X-ray flux in the energy range 1–22 keV was ~1.5 times that of the Crab Nebula on 1980 October 10. The spectral softening was shown during the course of observation. The daily average of the apparent pulse period showed a gradual decrease from 103.67 s to 103.61 s between October 9 and October 21 and stayed at the last value until the end of observation.

During the span of our observation, we obtained 188 epochs of pulse arrival time. The Doppler fitting under the assumption that the observed period change is due entirely to the orbital motion restricts the orbital parameters of the X-ray star. The lower limit of 40 days is obtained for the orbital period with 90% confidence level, whereas the upper limit of ~120 days is derived by the consideration of the mass function. A finite value of eccentricity $e \approx 0.2$–0.4 is required for the above range of orbital period.

The long pulse period of 103.79 s observed on 1980 September 25 by Hameury *et al.* (1981) indicates the existence of an intrinsic change of pulse period during the outburst. The observed pulse period change can be consistently explained, if the intrinsic period decreases at a rate of $\dot{P}/P \approx -2\times10^{-10}\ \mathrm{s}^{-1}$ with a decreasing rate of change roughly proportional to a diminishing luminosity. This is favorable to an orbital period around 100 days.

The present outburst seems to have occurred at 18 cycles after the 1975 April event, if the outburst recurs at an interval of ~110 days as listed in Table 1. The present pulse arrival time analysis indicates that these outbursts occurred near the time of periastorn passage. The periodic occurrence of outburst near the periastron passage in a highly eccentric orbit may be considered as a possible explanation of the recurrent transient X-ray source A0535+26.

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REFERENCES

Avni, Y., Fabian, A., and Pringle, J. 1976, *M.N.R.A.S.*, **175**, 297.

Bradt, H., *et al.* 1976, *Ap. J.* (*Letters*), **204**, L67.

Chartres, M., and Li, F. 1977, *IAU Circ.*, 3154.

Clark, G., and Chartres, M. 1977, *IAU Circ.*, 3208.

Coe, M. J., Carpenter, G. F., Engel, A. R., and Quenby, J. J. 1975, *Nature*, **256**, 630.

Fabbiano, G., Bradt, H. V., Doxsey, R. E., Gursky, H., Schwartz, D. A., and Schwartz, J. 1978, *Ap. J.* (*Letters*), **221**, L49.

Forman, W., Jones, C., and Tananbaum, H. 1976, *Ap. J.* (*Letters*), **206**, L29.

Giangrande, A., Giovannelli, F., Bartolini, C., Guarnieri, A., and Piccioni, A. 1980, *Astr. Ap. Suppl.*, **40**, 289.

Guarnieri, A., 1981, private communication.

Hameury, J. M., Boclet, D., Durouchoux, P., Cline, T., Paciesas, W., Teegarden, B., Tueller, J., and Haymes, R., 1981, *Proc. 17th Int. Cosmic Ray Conf.*, **9**, 21.

Hayakawa, S. 1981, *Space Sci. Rev.*, **29**, 373.

Hutchings, J. B., Bernard, J. E., Crampton, D., and Cowley, A. P. 1978, *Ap. J.*, **223**, 530.

Jones, C., Forman, W., Tananbaum, H., and Turner, M. J. L. 1976, *Ap. J.* (*Letters*), **210**, L9.

Kaluzienski, L. J., and Holt, S. S. 1978, *IAU Circ.*, 3259.

Kaluzienski, L. J., Holt, S. S., Boldt, E. A., and Serlemitsos, P. J. 1975, *Nature*, **256**, 633.

______. 1977, *Nature*, **265**, 606.

Kelley, R., Rappaport, S., and Petre, R. 1980, *Ap. J.*, **238**, 699.

Kondo, I., *et al.* 1981, *Space Sci. Instr.*, **5**, 211.

Koyama, K., *et al.* 1981, *Ap. J.* (*Letters*), **247**, L27.

Li, F., Rappaport, S., Clark, G. W., and Jernigan, J. G. 1979, *Ap. J.*, **228**, 893.

Maraschi, L., Huckle, H. E., Ives, J. C., and Sanford, P. W. 1976, *Nature*, **263**, 34.

Margon, B., Nelson, J., Chanan, G., Thorstensen, J. R., and Bowyer, S. 1977, *Ap. J.*, **216**, 811.

Matilsky, T., Bradt, H. V., Buff, J., Clark, G. W., Jernigan, J. G., Joss, P. C., Laufer, B., and McClintock, J. 1976, *Ap. J.* (*Letters*), **210**, L127.

Matsuoka, M., *et al.* 1980, *Ap. J.* (*Letters*), **240**, L137.

Murakami, T., *et al.* 1980, *Ap. J.* (*Letters*), **240**, L143.

Nagase, F. 1981, *Space Sci. Rev.*, **30**, 395.

Nagase, F., *et al.* 1982, in preparation.

Okuda, T., and Sakashita, S. 1977, *Ap. Space Sci.*, **47**, 385.

Persi, P., Ferrari-Toniolo, M., Spada, G., Conti, G., Di Benedetto, P., Tanzi, E. G., and Tarenghi, M. 1979, *M.N.R.A.S.*, **187**, 293.

Pounds, K. A. 1976, *Comments Ap.*, **6**, 145.

Rappaport, S., Clark, G. W., Cominsky, L., Joss, P. C., and Li, F. 1978, *Ap. J.* (*Letters*), **224**, L1.

Rappaport, S., Joss, P.C., Bradt, H., Clark, G. W., and Jernigan, J. G. 1976, *Ap. J.* (*Letters*), **208**, L119.

Rappaport, S., and van den Heuvel, E. P. J. 1981, in *IAU Symposium 98*, *Be Stars*, ed. M. Jaschek and H. G. Groth (Dordrecht: Reidel), in press.

Ricker, G. R., Scheepmaker, A., Ballintine, J. E., Doty, J. P., Kriss, G. A., Ryckman, S. G., and Lewin, W. H. G. 1976, *Ap. J.* (*Letters*), **204**, L73.

Ricketts, M. J., Pounds, K. A., and Turner, M. J. L. 1975, *Nature*, **257**, 657.

Ricketts, M. J., Turner, M. J. L., Page, C. G., and Pounds, K. A. 1975, *Nature*, **256**, 631.

Rose, L. A., Pravdo, S. H., Kaluzinski, L. J., Marshall, F. E., Holt, S. S., Boldt, E. A., Rothschild, R. E., and Serlemitsos, P. J. 1979, *Ap. J.*, **231**, 919.

Rosenberg, F. D., Eyles, C. J., Skinner, F. K., and Willmore, A. P. 1975, *Nature*, **256**, 628.

Shapiro, S. L., and Lightman, A. P. 1976, *Ap. J.*, **204**, 555.

Sims, M. R., and Fraser, F. W. 1979, *IAU Circ.*, 3339.

Stier, M., and Liller, W. 1976, *Ap. J.*, **206**, 257.

Watson, M. G., Warwick, R. S., and Ricketts, M. J. 1981, *M.N.R.A.S.*, **195**, 197.

White, N. E., Mason, K. O., and Sanford, P. W. 1978, *M.N.R.A.S.*, **184**, 67p.

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