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PULSE CHARACTERISTICS OF THE X-RAY PULSAR 4U 1907+09

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ABSTRACT

The X-ray pulsar 4U 1907+09 was observed in the 2–18 keV energy band with the Indian X-Ray Astronomy Experiment (IXAE) during 1996 August and again in 1998 June. From the timing measurements, the spin-down rate of the neutron star is measured to be $+0.23 \pm 0.01$ s yr^{-1}. A straight-line fit to the historical pulse period data indicates that the pulsar has been in a monotonic phase of spin-down since its discovery. The day-to-day pulse profile indicates some variations during its 8.4 day binary period. The average profile obtained from these observations shows a double-pulse shape with a pronounced asymmetric primary separated by a dip from a relatively weaker but broad secondary. These profiles show a closer resemblance to the pulse shape obtained with the recent observations with the *Rossi X-Ray Timing Explorer* (*RXTE*) during 1996 February, as compared to the earlier observations carried out six to 13 years earlier. A secondary flare of 88 mcrab intensity was detected during the IXAE observations in 1996 August. A detailed analysis of the flare data shows the presence of transient 14.4 s oscillations, which may be quasi-periodic during the flaring activity but have a period different from the earlier reported oscillations of 18.2 s as detected by *RXTE* during the flare of 1996 February. These results, therefore, strengthen the evidence for the presence of a transient accretion disk around the neutron star during the flare, which may be responsible for the continuous slowing down of the pulsar. The studies of such transient quasi-periodic oscillations during flaring activities of 4U 1907+09 thus provide opportunities for understanding the transient behavior of the accretion disk and its physical characteristics.

Subject headings: accretion, accretion disks — pulsars: individual (4U 1907+09) — stars: neutron — X-rays: stars

1. INTRODUCTION

The X-ray source 4U 1907+09 has been observed from time to time by various X-ray satellites since its discovery in the *Uhuru* survey (Giacconi et al. 1971; Schwartz et al. 1972). Modulation of X-ray flux with a period of 8.38 days detected first by *Ariel 5* observations (Marshall & Ricketts 1980) and confirmed with *Tenma* (Makishima et al. 1984) and *EXOSAT* (Cook & Page 1987) is attributed to the orbital motion of the X-ray source around its companion star. The optical counterpart of 4U 1907+09 was identified by Schwartz et al. (1980), who suggested that it is an OB supergiant. The Hα emission detected from the companion was associated with the stellar wind of the OB supergiant. However, Makishima et al. (1984) argued that the occurrence of two X-ray outbursts separated by 0.45 in phase in every binary cycle of 8.38 days and the longer pulse period of 4U 1907+09 are indicative of a Be X-ray binary, as suggested in the model of Shibazaki (1982). Later observations of the optical counterpart (Iye 1986) showed variation in Hα emission, which is a well-known characteristic of Be stars (Andrillat & Fehrenbach 1982). These arguments, therefore, suggest that the companion star is more likely to be a Be star than an OB supergiant. However, other characteristics of Be systems such as longer duration giant outburst activities, as seen in the case of A0535+26 (Motch et al. 1991), and high eccentricity are not observed in 4U 1907+09. The observations of the wind-fed X-ray pulsar GX 301−2 (Pravdo et al. 1995; Chichkov et al. 1995; Koh et al. 1997), having an OB supergiant companion, consistently show two flares per orbit as in the case of 4U 1907+09. The possibility of the companion star in 4U 1907+09 being an OB supergiant cannot, therefore, be ruled out completely.

X-ray pulsations with a period of 437.5 s were discovered from 4U 1907+09 from the *Tenma* observations (Makishima et al. 1984). The timing measurements carried out subsequently by *EXOSAT* (Cook & Page 1987) and the *Rossi X-Ray Timing Explorer* (*RXTE*; in 't Zand, Baykal, & Strohmayer 1998) showed continuous spin-down of the neutron star. Refined orbital parameters of the binary were derived recently from *RXTE* data. Transient oscillations with a period of 18.2 s were detected during a secondary outburst in the *RXTE* data. These have been suggested to be associated with the occurrence of a transient retrograde accretion disk responsible for the slowing down of the pulsar (in 't Zand et al. 1998). Based on the detection of a cyclotron resonance line, the surface polar magnetic field of the neutron star in 4U 1907+09 was determined to be (2.1–2.5) × 10^{12} G (Makishima & Mihara 1992; Cusumano et al. 1998).

In this paper, we report the results obtained from two observations of 4U 1907+09, separated by a time span of about two years, in the 2–18 keV energy band with the Indian X-Ray Astronomy Experiment (IXAE). The pulsar timing measurements and the pulse profiles are presented here. The day-to-day pulse profiles obtained for six consecutive days of observations during the 8.4 day binary period of the pulsar are presented here for comparison. The IXAE detected a secondary outburst during the 1996 observations. The timing analysis of the outburst data shows the

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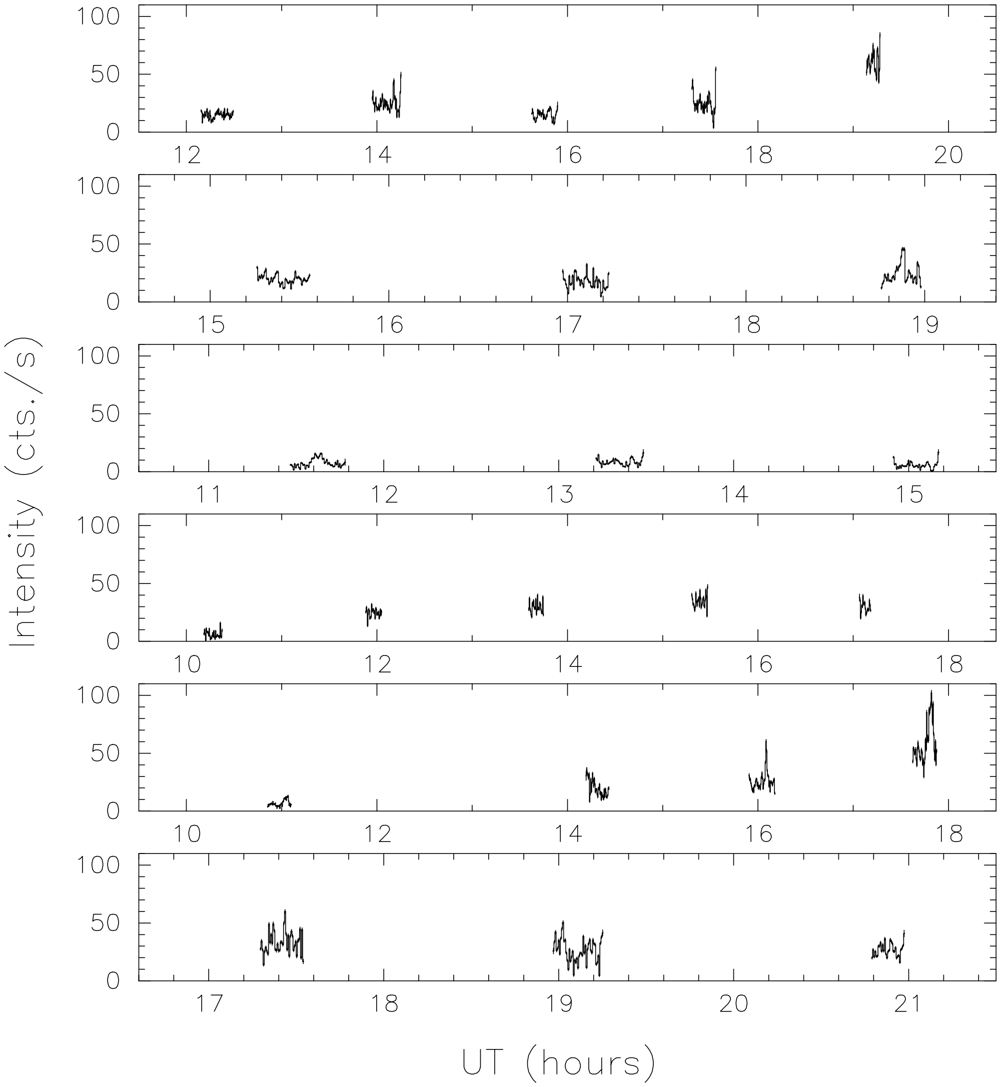

FIG. 1.—X-ray light curves of 4U 1907+09 in the 2–18 keV energy band obtained by IXAE in 1996 August 4–9 (*from top to bottom*) are shown with a time binning of 22 s.

presence of 14.4 s transient oscillations. The origin of these oscillations and its implications are discussed in this paper. In § 2 we briefly describe IXAE instruments and observations along with operational details. The analysis of the data along with the results obtained are discussed in § 3. In § 4 the implications of the transient oscillations and disk formation leading to continuous spinning-down of the pulsar are discussed. Finally, the main results obtained from the IXAE observations are summarized in § 5 of this paper.

2. INSTRUMENT AND OBSERVATIONS

The Indian X-Ray Astronomy Experiment on board the *IRS-P3* satellite was launched from the Shriharikota range in India on 1996 March 21. The complete instrument and operational details are described in Agrawal et al. (1997) and Agrawal (1998). The X-ray instrument consists of three identical, co-aligned pointed proportional counters (PPCs) sensitive in the energy range of 2–18 keV with an effective area of about 1200 cm^2 and a field of view (FOV) of 2°.3 × 2°.3 FWHM. The PPCs can be operated in either spectral mode or pulsar mode. A variety of sampling rates can be utilized for spectral mode accumulation. The PPCs were operated in the nominal mode with a sampling time of 1.02 s during the observations of 4U 1907+09. Due to the 830 km nearly circular polar orbit of the *IRS-P3* satellite, restrictions are placed on the exposure time due to the South Atlantic Anomaly (SAA) zone and the presence of very high charge particle fluxes at higher latitudes. Therefore, for safe operation, the PPCs are operated in the latitude range of −30° to 50°, resulting in 15–20 minutes of useful data in each of the five consecutive orbits which do not pass through the SAA region.

The observation of 4U 1907+09 was carried out in 1996 August 4–9 and again in 1998 May 29 to June 2. A star tracker on board the *IRS-P3* satellite, co-aligned with the view axes of the PPCs, is used to make pointed-mode observations with an accuracy of better than 0°.1.

3. ANALYSIS AND RESULTS

Five segments of binned data are acquired for each day of observation by each PPC. The data of each PPC are stored in its individual memory along with the timing and housekeeping information. The timing and vignetting corrections and also background subtraction were carried out before combining the data of the three PPCs. The observations were carried out with an offset of 0°.7 from 4U 1907+09 to avoid contamination from bright neighboring source GRS 1915+105, which is 1°.77 away from 4U 1907+09. Other cataloged X-ray sources within the FOV are relatively weak, and it is likely that they made only a marginal (~5%) contribution to the observed count rates. Whenever data from a particular PPC was not available, data from the two PPCs were added and normalized for three PPCs along with the corresponding uncertainties, which were propagated accordingly. This helps in direct comparison of the data for different observations.

3.1. *The X-Ray Light Curves*

The X-ray light curves of 4U 1907+09 in the 2–18 keV energy band, obtained from six consecutive days of 1996 observations, are shown in Figure 1. The data from all three PPCs were added and used for generating the light curves. The IXAE observations cover a major part of the 8.4 day binary period from phase 0.02 to 0.64, the phase calculation being based on assumption of phase zero at periastron. Two flares, termed the primary and secondary flares, are usually seen in the binary light curves of 4U 1907+09, as reported earlier (Marshall & Ricketts 1980; Cook & Page 1987). We have calculated the flare epoch using the binary ephemeris taken from the *RXTE* and *Tenma* data (in 't Zand et al. 1998; Makishima et al. 1984). Based on this, the primary flare is expected to occur on August 4 at 23 ± 3 hr (UT), while the secondary flare is predicted to occur on August 8 at 16 ± 3 hr (UT). The light curve obtained on 1996 August 4 shows an increase in the average counting rate near 19 hr, indicating the start of the primary flare. The peak of the primary flare was missed due to lack of useful data from the IXAE observations in the subsequent orbits. The sudden increase of source intensity on 1996 August 8 around 18 hr is identified as being due to the secondary flare. The peak intensity of 110 counts s^{-1} corresponds to the source intensity of about 88 mcrab. The observed peak intensity of the secondary flare is comparable to the *RXTE* observations, where the source intensity increased to about 100 mcrab (in 't Zand et al. 1998). A detailed light curve of the secondary flare is given in Figure 2 for the 2–18 keV energy range with a bin time of 10 s. We notice a remarkable similarity in the shape of the light curve of the source with respect to the *RXTE* flare (Fig. 6, in 't Zand et al. 1998). We also observe non-Poissonian variations in counting rates in the light curve during the flaring interval, indicating the presence of additional signal in the data.

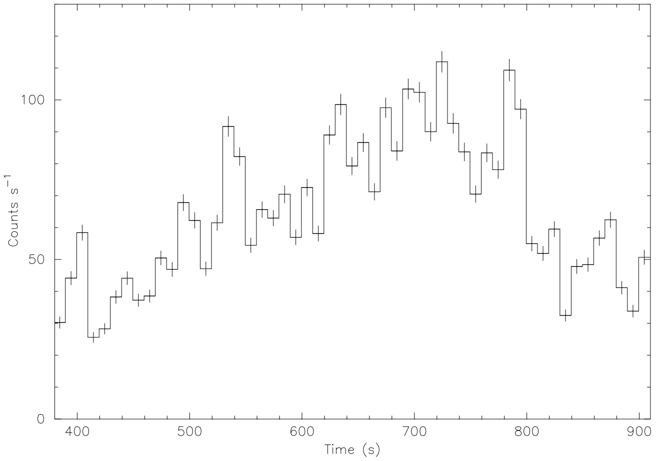

FIG. 2.—Light curve of a flare observed by IXAE is shown with 10 s bin time. The peak intensity of 110 counts s^{-1} corresponds to 88 mcrab source intensity.

3.2. *The Pulsar Period and the Pulse Profiles*

The photon arrival times were corrected for the Earth's motion around the Sun and the satellite's motion around the Earth with respect to the solar system barycenter. The *RXTE* orbital delay time curve (Fig. 3, in 't Zand et al. 1998) was used to correct for the pulse timing due to the orbital motion of the neutron star in the binary system. The epoch folding technique was used to determine the pulse period of the source. We have also used the method described by Horne & Baliunas (1986) and Scargle (1982), which uses a normalization for the power such that the false alarm probability can be directly evaluated. The pulse period and uncertainty in the period derived with the two techniques were found to be consistent. The pulse periods measured with the IXAE along with earlier measurements carried out with other X-ray satellites have been compiled in Table 1. The quoted uncertainty in the pulse period corresponds to a 1 σ confidence level. The period derivative was estimated using the value of the pulse period first measured from the *Tenma* observations. A best-fit straight line to all the measured spin periods and the residuals to the fit are shown in Figure 3. The average value of $\dot{P}$ was found to be 0.234 ± 0.001 s yr^{-1} at the 90% confidence level. This is consistent with the value of $\dot{P} = 0.23 \pm 0.01$ obtained from the period measured with the IXAE. The pulsar in 4U 1907+09 has thus been monotonically spinning down since its discovery.

TABLE 1

PULSE PERIOD HISTORY OF 4U 1907+09

Observation	Satellite	MJD	Pulse Period (s)	Derivative[a] (s yr^{-1})	References
1983 Aug......	*Tenma*	45,576	437.483 ± 0.004	...	1
1984 Jun	*EXOSAT*	45,850	437.649 ± 0.019	0.221 ± 0.026	2
1990 Sep	*Ginga*	48,156.6	439.19 ± 0.02	0.241 ± 0.003	3
1996 Feb	*RXTE*	50,134	440.341 ± 0.014	0.229 ± 0.005	4
1996 Aug......	IXAE	50,302[b]	440.53 ± 0.01	0.2353 ± 0.0008	5
1998 Jun	IXAE	50,665[b]	440.95 ± 0.01	0.2348 ± 0.0007	5

[a] The period derivatives were calculated with respect to the *Tenma* observation in 1983 August.

[b] Average of MJD for the IXAE observations is given.

REFERENCES.—(1) Makishima et al. 1984. (2) Cook & Page 1987. (3) Mihara 1995. (4) in 't Zand et al. 1998. (5) Present work.

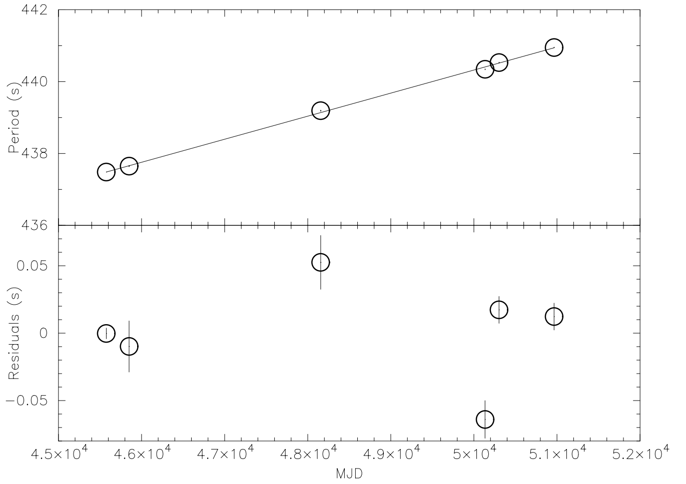

FIG. 3.—Pulse period history plot of 4U 1907+09 obtained from *Tenma*, *EXOSAT*, *Ginga*, *RXTE*, and two IXAE observations, respectively, along with respective errors that are shown within the symbols by vertical lines. A straight-line fit is shown as a continuous line and the residuals to the fit are shown in the bottom panel.

The X-ray pulse profiles of 4U 1907+09 for individual days were obtained by folding the data with the best-fit period and are shown along with the mean orbital binary phase in Figure 4. The pulse profiles for individual days from 1996 August 4 to 9 covering about 60% of the binary phase have been obtained for the first time after *EXOSAT* observations in 1984 (Cook & Page 1987). There are indications of variation in the pulse shape on different days. In particular, the relative intensities of main pulse and interpulse are found to be changing from one day to next. The profile obtained, including the outburst data of 1996 August 8 ($\phi = 0.49$), shows a pronounced double-pulse shape with almost equal amplitudes in both the pulses. Moreover, the peak intensities of the main pulse and the interpulse are also found to vary with the binary phases. Dips are noticed in the interpulse affecting its shape. The average pulse fraction is, however, found to be about 30% on all the days. Similar variations in pulse shape have been observed in the *EXOSAT* data. The average pulse profiles for the 1996 and 1998 observations were obtained by adding all the phase-matched individual profiles and are shown in Figure 5. The 1 σ errors on the folded data were derived from the counting statistics. The average X-ray pulse profiles obtained from the IXAE observations have a pronounced double-pulse shape. The two pulse shapes show marked similarity except for an indication of a marginally broader primary pulse in 1998. This could be intrinsic to the source due to some change in the accretion process as the average intensity of the source during 1996 (source flux $\approx$15 mcrab) is found to be higher than that in 1998 (source flux $\approx$10 mcrab). The pulse shape derived from IXAE data of 1996 has a close resemblance with that from the *RXTE* observation of 1996 February (in 't Zand et al. 1998). The measured pulse fraction in the 2–18 keV energy band from IXAE is found to be 30% ± 1% in 1996 and 25% ± 1% in 1998.

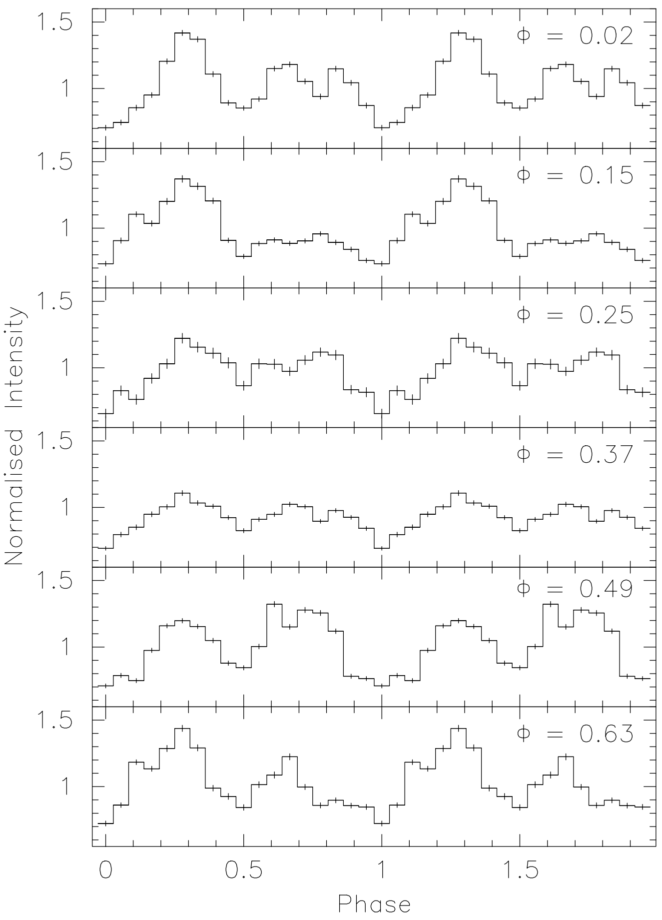

FIG. 4.—IXAE pulse profiles of 4U 1907+09 in the 2–18 keV energy band obtained for six consecutive days of observations between 1996 August 4 and 9 (*top to bottom panels*). The mean binary phases (ϕ) of these observations are indicated in the figure.

3.3. *The Transient Oscillations during the Flare*

The complete set of observations of 4U 1907+09 in 1996 and 1998 were analyzed to detect the presence of any transient oscillations similar to those reported from the *RXTE* observation. The power spectrum constructed in the frequency range of 0.001–0.5 Hz indicates the presence of a prominent peak at 0.069 Hz only in the secondary flare data of 1996 August 8. This corresponds to a pulsation period of 14.4 s compared to the 18.2 s oscillations detected with the *RXTE* in the secondary flare data (in 't Zand et al. 1998).

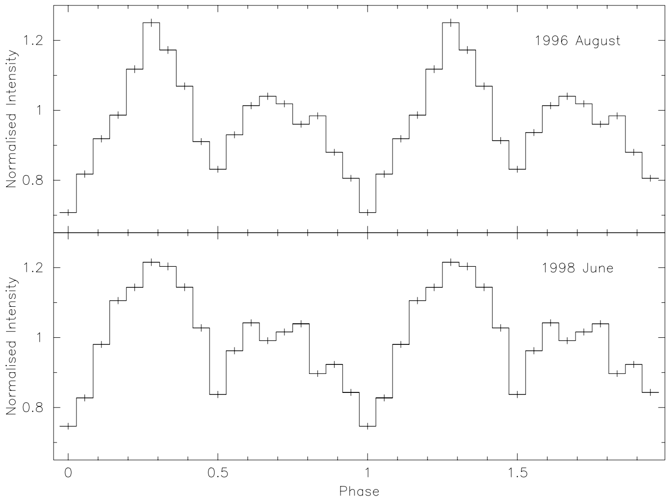

FIG. 5.—Average pulse profile of 4U 1907+09 in the 2–18 keV energy band obtained from 1996 August and 1998 June observations with IXAE.

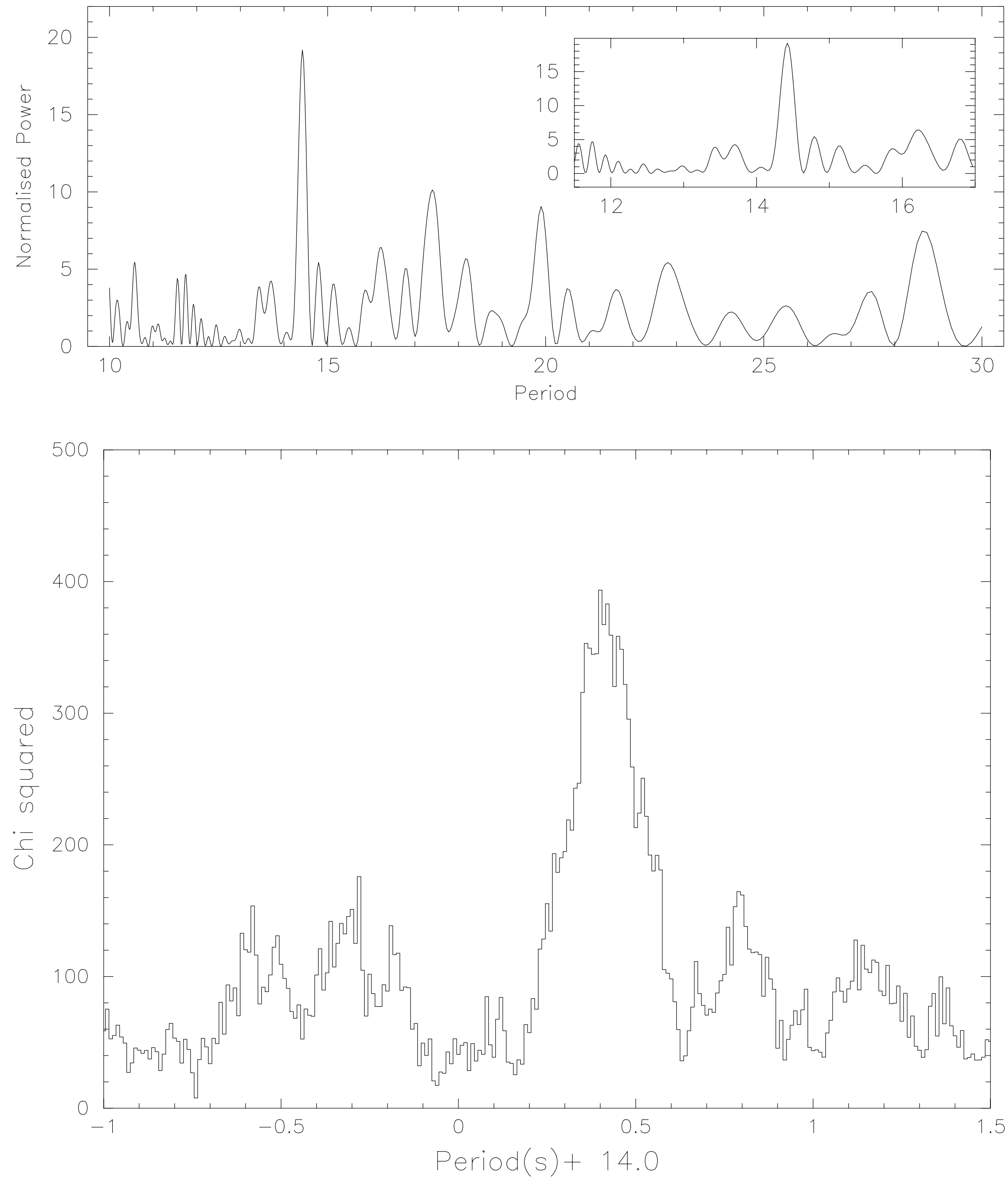

FIG. 6.—Periodogram constructed using the complete 860 s of flare data of 1996 August 8 (*top panel*); 14.4 s pulsations detected applying epoch folding technique on the flare data (*bottom panel*).

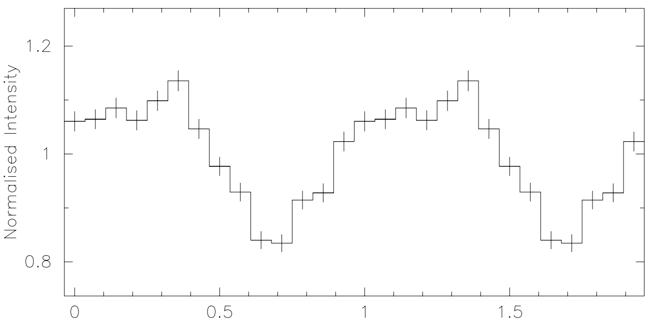

FIG. 7.—Folded light curve of the flare, folded with 14.4 s period of transient oscillation.

The periodogram is shown in Figure 6 (*top panel*), which clearly indicates the 14.4 s pulsation peak along with its weaker second harmonic corresponding to 28.8 s. The presence of the 14.4 s pulsation was also confirmed using the epoch folding method and the same is shown in Figure 6 (*bottom panel*). The epoch folding method uses 14 bins for the pulse period, and the observed χ^2 peak (400) at 14.4 s corresponds to a reduced χ^2 value of 30. This has a negligible probability of occurrence by chance. However, the χ^2 probability calculated does not take into account other random variations such as pulse period variation. The periodogram method gives a false alarm probability (FAP) of 8.6×10^{-6} for the peak power at 14.4 s. The other peaks in the periodogram at 17.4 s, 19.9 s, and 28.8 s have FAP of

0.07, 0.2, and 0.6, respectively, which are statistically not significant. A careful search of other data segments did not show evidence for presence of such pulsations at any other time during the IXAE observations. The pulse profile presented in Figure 7 was obtained by folding the data with the 14.4 s period. A double sinusoidal provides a better fit to this profile as indicated by reduced $\chi^2 = 1.6$ for 5 degrees of freedom compared to a single-sinusoidal function which gives reduced $\chi^2 = 2.8$ for 8 degrees of freedom.

4. DISCUSSION

4.1. *Deceleration of the Pulsar*

Many accreting X-ray pulsars show systematic spin-up and spin-down behavior and vice versa over a long time period. These include GX 1+4 ($P/\dot{P} = 90$ yr), 4U 1626−67 ($P/\dot{P} = 5 \times 10^3$ yr), Vela X-1 ($P/\dot{P} = 6 \times 10^3$ yr), etc. (Bildsten et al. 1997). The X-ray pulsar 4U 1907+09 ($P/\dot{P} = 2 \times 10^3$ yr), however, has exhibited continuous spin-down since its discovery. We consider two scenarios for the continuous spin-down of 4U 1907+09: inhibition of accretion and formation of a transient accretion disk to explain the transient 14 s oscillations.

The slowing down behavior of pulsars could be due to a lower accretion rate and the resulting centrifugal inhibition of accretion, occurring when magnetospheric radius r_m extends closer to the corotation radius $r_{\rm co}$ (the so-called propeller effect). The infalling material is flung away carrying part of the rotational energy extracted from the neutron star, resulting in slowing down of the neutron star.

The minimum luminosity $L_{\rm X}({\rm min})$ below which an X-ray pulsar "turns off" due to centrifugal inhibition of accretion or the propeller effect can be derived from the condition $r_m = r_{\rm co}$ (Illarionov & Sunyaev 1975):

$$L_{\rm X}({\rm min}) \approx 2 \times 10^{37}(R/10^6\ {\rm cm})^{-1}(M/1.4\ M_\odot)^{-2/3} \times (\mu/10^{30}\ {\rm G\ cm^3})^2(P_s/1\ {\rm s})^{-7/3}\ {\rm ergs\ s^{-1}}\ . \quad (1)$$

The magnetic moment (μ) of the neutron star for a dipole-like field configuration is given by $\mu = B \times R^3$, where B is surface polar magnetic filed strength and R is the radius of the neutron star. From cyclotron resonance features, Cusumano et al. (1998) have derived $B = 2.1 \times 10^{12}$ G (with $\sim$2% uncertainty at a 1 σ confidence level), which gives $\mu = 2.1 \times 10^{30}$ G cm^3 for a 10 km radius of the neutron star. From this we obtain $L_{\rm X}({\rm min}) = 6 \times 10^{31}$ ergs s^{-1} for 4U 1907+09. The pulsar luminosity must go down below this limiting value for the propeller effect to prevail. The detection of this limiting luminosity is below the minimum detection limit of the IXAE. However, in 't Zand, Strohmayer, & Baykal (1997) reported an intermittent decline in the X-ray intensity below the detection limit during its binary cycle. This phenomenon has been defined as dipping activity. The dip interval is found to vary from a few minutes to 1.5 hr, covering about 20% of the observation time. The minimum luminosity $L_{\rm X}({\rm min})$ for inhibition of accretion in 4U 1907+09 corresponds to about 1.4×10^{-3} counts s^{-1} for *RXTE* and 1.4×10^{-4} counts s^{-1} for IXAE. Since these count rates are well below the background rates of the detectors, it is not possible to detect such an "intermittent propeller effect," if it is taking place at all, during the dipping activities in each of its orbital cycles. The intermittent propeller effect, if it takes place in most of the binary orbits, may lead to the observed uniform spin-down in the pulsar. However, a comparison with Be transient source GRO J1008−57 (Macomb, Shrader, & Schultz 1994) indicates that even though the source luminosity declined by a factor of about 100 from the peak value, the centrifugal inhibition of accretion did not take place. This argument, if valid for the case of 4U 1907+09, will violate the above explanation of spinning-down resulting from inhibition of accretion, which is applicable to many Be binary pulsars.

The 14.4 s oscillations observed during the secondary flare of 4U 1907+09 by the IXAE and the 18.2 s oscillations detected during the secondary flare by the *RXTE* in 1996 February appear to be of the quasi-periodic nature. These quasi-periodic oscillations (QPOs) in pulsars represent characteristic properties of an accretion disk around a neutron star (see, e.g., the beat frequency model of Alpar & Shaham 1985) and, therefore, provide evidence for the formation of a transient accretion disk around the neutron star in 4U 1907+09. We examine below a scenario in which the continuous spin-down may be explained as due to the formation of a retrograde transient disk.

The condition for formation of such a transient accretion disk has been given by Lamb (1989) and Nelson et al. (1997). The observations also indicate the presence of such a transient accretion disk in Be/binary pulsars like 4U 0115+63 (Soong & Swank 1989), EXO 2030+375 (Angelini, Stella, & Parmar 1989), and V0332+53 (Takeshima et al. 1994). From the condition of disk formation one can derive the radius r_d of material in the putative disk (Lamb 1989; Ghosh 1998),

$$r_d = (GM/4\pi^2\nu_{\rm QPO}^2)^{1/3}\ , \quad (2)$$

where M is the mass of the neutron star and $\nu_{\rm QPO}$ is the QPO frequency. For 4U 1907+09, r_d is calculated to be 9.9×10^8 cm for a 1.4 $M_\odot$ neutron star.

The corotation radius $r_{\rm co}$ of an X-ray pulsar is derived by equating the Keplerian velocity to the corotating Keplerian velocity. Therefore,

$$r_{\rm co} = 1.7 \times 10^8 P^{2/3}(M/1.4\ M_\odot)^{1/3}\ {\rm cm}\ , \quad (3)$$

where P is the spin period of the neutron star. Using pulse period $P = 440.53$ s and assuming a neutron star mass of $M = 1.4\ M_\odot$, one obtains the corotation radius $r_{\rm co}$ for 4U 1907+09 as 9.8×10^9 cm. It is therefore evident that the disk radius is an order of magnitude smaller than the corotation radius.

The expression for magnetospheric radius r_m has, to a good approximation, been derived for a dipole field configuration of the neutron star at large distance (Ghosh & Lamb 1991) as

$$r_m = 2.2 \times 10^8(L_{\rm X}/3.1 \times 10^{37}\ {\rm ergs\ s^{-1}})^{-2/7} \times (M/1.4\ M_\odot)^{1/7}(B/2.1 \times 10^{12}\ {\rm G})^{4/7} \times (R/10^6\ {\rm cm})^{10/7}\ {\rm cm}\ , \quad (4)$$

where $L_{\rm X}$ is the bolometric X-ray luminosity. For a 1.4 $M_\odot$ neutron star with a radius of 10^6 cm and using $B = 2.1 \times 10^{12}$ G (Cusumano et al. 1998), we can determine the magnetospheric radius of 4U 1907+09 during the IXAE observations. The 4U 1907+09 luminosity corresponding to the peak of the secondary flare detected during the IXAE observation is estimated to be 3.5×10^{36} ergs s^{-1} for an assumed source distance of 4 kpc (van Kerkwijk, van Oijen, & van den Heuvel 1989). Using this luminosity, the magnetospheric radius r_m is calculated to be 4.1×10^8 cm. We thus observe that the corotation radius $r_{\rm co}$ is about 25 times the magnetospheric radius r_m at the observed luminosity. Although the estimated value of magnetospheric radius may have large uncertainty, it does indicate that the accretion disk can be formed close enough to the magnetosphere to account for the 14.4 s oscillations observed during the IXAE observations.

The formation of such a disk may supply torque to the neutron star. The observed torque of the pulsar can be expressed as

$$N_0 = 2\pi I\dot{\nu}, \tag{5}$$

where $I = 10^{45}$ g cm^2 is the moment of inertia of the neutron star and $\dot{\nu}$ is the rate of change of frequency. The measured value of $\dot{P} = 0.23$ s yr^{-1} corresponds to $\dot{\nu} = 3.7576 \times 10^{-14}$ Hz s^{-1}. The observed torque is therefore estimated to be 2.36×10^{32} g cm^2 s^{-2}.

The expected torque ($N_{\rm char}$) on the neutron star from a transient disk can be calculated using the expression

$$N_{\rm char} = \eta\dot{M}(GMR_d)^{1/2} , \tag{6}$$

where $\dot{M}$ is the mass accretion rate and η is the duty cycle for the applied torque. The mass accretion rate can be calculated from the observed luminosity using

$$L_{37} = 1.33\dot{M}_{17}(M/M_\odot)R_6^{-1} \text{ ergs s}^{-1} . \tag{7}$$

The estimated value of $\dot{M}$ during the flare is 1.8×10^{16} g s^{-1}. Using these parameters, the value of $N_{\rm char}$ is found to be $\eta(80 \times 10^{32})$ g cm^2 s^{-2}.

By equating the two torques, the value of η is found to be 0.029. This corresponds to a duration of 0.24 days for the binary period of 8.38 days, and a torque of this duration is sufficient to cause the slowing down of the pulsar. The observation of the IXAE flare (860 s) is for a much smaller duration compared to the duty cycle estimated above. However, the actual duration of the flare may be much longer as we can only acquire limited data from the IXAE. Moreover, the average duration of the flares over many binary cycles is of the order of 0.3 of the orbital phase (Marshall & Ricketts 1980; Makishima et al. 1984). Therefore, formation of a retrograde accretion disk of the above estimated duration during the flare may possibly supply negative torque sufficient to explain the observed monotonic spin-down of the pulsar.

The X-ray observations of flaring activity in 4U 1907+09 (Marshall & Ricketts 1980; Makishima et al. 1984; Cook & Page 1987) at regular intervals during each of its orbital cycles suggests that its companion is likely to be a Be star, on the basis of the model of Shibazaki (1982). The observed X-ray flares with a difference in phase of 0.45 orbital period may result from the pulsar intersecting the extended disk of the Be star twice in each orbital cycle. The variation in Hα emission is a well-known characteristic of Be stars (Andrillat & Fehrenbach 1982). The optical observations of Iye (1986) shows variable Hα emission with large equivalent width, which is an important characteristics of Be stars. These characteristics are consistent with a Be star scenario rather than a B supergiant (Klein & Castor 1978; Grindlay, Petro, & McClintock 1984). Similar variations have also been observed in another X-ray binary pulsar with a Be companion, X0331+53. However, the relationship between the spin and orbital periods in the Be binary pulsars given by Corbet (1984) does not hold in the case of 4U 1907+09. The large spin-down rate is probably taking it away from the equilibrium and the majority of sources in the Corbet diagram. However, the argument that the companion may be an OB supergiant cannot be completely ruled out since X-ray flaring activity similar to that of 4U 1907+09 has also been observed in GX 301−2, another wind-fed accreting X-ray pulsar with a supergiant companion (Pravdo et al. 1995; Chichkov et al. 1995; Koh et al. 1997). These observations suggest that wind from the companion may not be isotropic but rather channeled along the equatorial plane with enhanced mass density responsible for flaring while the neutron star traverses this plane twice per orbit at an inclination.

4.2. *Application of QPO Models*

Quasi-periodic oscillations have been observed in many accretion-powered X-ray binary pulsars. These QPOs have frequencies in the range of 10–400 mHz, which are considerably lower than those of both the low (6–50 Hz) frequency QPOs and the high (300–1200 Hz) frequency QPOs observed in low-mass X-ray binaries (van der Klis 1995, 1997). A list of the X-ray pulsars in which QPOs have been detected so far is given in Table 2 along with other QPO parameters. There are various models described to explain the QPO phenomenon (Lewin, van Paradijs, & van der Klis 1988). These models broadly fall into three categories: the Keplerian frequency model (van der Klis et al. 1987), the beat frequency model involving Keplerian motion and neutron star rotation (Alpar & Shaham 1985), and accretion flow instabilities (Fronter, Lamb, & Miller 1989; Lamb 1988). The last model had been proposed to explain 6 Hz normal branch QPOs in Z-type sources and implies an X-ray luminosity close to the Eddington limit (Hasinger & van der Klis 1989). Since the observed luminosity of 4U 1907+09 is well below the Eddington limit, this model may not be applicable in this case.

We now consider the Keplerian frequency model and apply it to a transient disk that could be formed in 4U 1907+09. In this model the QPOs are produced due to some inhomogeneities in the Keplerian disk that attenuate the pulsar beam regularly. The QPO center frequency is given by the Keplerian frequency at the inner edge of the accretion disk. Since the observed QPO frequency (69 mHz) of 4U 1907+09 is more than the rotation frequency (2.27 mHz) of the neutron star, it implies that this model may be applicable to this pulsar.

In the beat frequency model, the QPOs are produced when the material in fall onto the pulsar from the disk is modulated at the Keplerian frequency. The QPO center frequency $\nu_{\rm QPO} = \nu_k - \nu_s$ is the difference between the Keplerian orbital frequency ν_k of material at the inner edge of the accretion disk and the spin frequency ν_s of the neutron star. The radius r_d of the inner edge of the disk can be determined using Kepler's third law and is expressed as in equation (2). Therefore, in both these models, the radius of the inner edge (r_d) of the accretion disk depends on the QPO frequency ($\nu_{\rm QPO}$) and the mass of the neutron star (M). The Keplerian frequency corresponding to a 14.4 s oscillation is thus found to be

$$\nu_k = 0.069 + 0.00227 = 0.071 \text{ Hz} . \tag{8}$$

From the accretion disk model (Ghosh & Lamb 1979), the Keplerian frequency at the magnetosphere boundary is estimated to be

$$\nu_k = 0.74\mu_{30}^{-6/7}L_{37}^{3/7} . \tag{9}$$

TABLE 2

PROPERTIES OF QPOs IN X-RAY PULSARS

Pulsar	ν_s (mHz)	$\nu_{\rm QPO}$ (mHz)	r_d (cm)	ν_k[a] (mHz)	ω_s[a]	References
X1626−67	130	48	1.3×10^9	178	0.73	1
GRO J1744−28	2100	400	3.1×10^8	2500	0.84	2
SMC X-1	1410	10	3.6×10^9	1420	0.99	3
X0115+63	277	62	1.1×10^9	339	0.82	4
V0332+53	229	51	1.2×10^9	280	0.82	5
Cen X-3	207	35	1.6×10^9	242	0.85	6
X Per	1.2	54	1.0×10^9	55.2	0.02	7
4U 1907+09	2.27	69	9.9×10^8	71.7	0.03	8
J1858+034	4.53	110	7.3×10^8	114.5	0.04	9
A0535+26	9.7	50	1.2×10^9	59.7	0.16	10
EXO 2030+375	24	200	4.9×10^8	224	0.11	11

[a] The quantities determined using magnetospheric beat frequency model (Alpar & Shaham 1985).

REFERENCES.—(1) Shinoda et al. 1990. (2) Zhang et al. 1996. (3) Angelini, Stella, & White 1991. (4) Soong & Swank 1989. (5) Takeshima et al. 1994. (6) Takeshima et al. 1991. (7) Takeshima 1997. (8) in 't Zand et al. 1998. (9) Paul & Rao 1998. (10) Finger, Wilson, & Harmon 1996. (11) Angelini et al. 1989.

Therefore, for a luminosity of 3.5×10^{36} ergs s^{-1}, the magnetic moment of the neutron star μ is found to be 9×10^{30} G cm^3. Using the measured magnetic field of 4U 1907+09 leads to a value of the neutron star radius $R = 1.6 \times 10^6$. Equation (4) gives the modified values of $r_m = 8 \times 10^8$ cm for the pulsar 4U 1907+09. Therefore, formation of an accretion disk close to the magnetosphere, which could account for the 14.4 s oscillations, is still plausible.

The fastness parameter (Ghosh & Lamb 1979) for the rotation of the neutron star, which is of central importance in the accretion torque theory (Ghosh 1996), is expressed as

$$\omega_s = \nu_s/\nu_k \; . \qquad (10)$$

To compare QPO parameters of 4U 1907+09 with those of other X-ray pulsars having QPOs, the important parameters of those pulsars are compiled in Table 2. The comparison shows that for a neutron star of mass 1.4 $M_\odot$, radii r_d are found in the range $\sim 10^8$–10^9 cm for QPOs in X-ray pulsars. Since accretion disks are expected to be terminated by the strong stellar magnetic field at the radii of 10^8–10^9 cm, the QPOs in X-ray pulsars are expected to provide information about the processes in the inner accretion disk around the neutron star. For 4U 1907+09, ω_s is found to be 0.03, which is close to the value obtained for X Per ($\omega_s = 0.02$) as given in Table 2. This is, however, different from the values of ω_s found for other Be binary pulsars, e.g., EXO 2030+375, X0115+63, and V0332+53.

Ghosh (1996, 1998) has shown that simultaneous data on torque and QPOs can serve as a good diagnostic for probing conditions in the inner accretion disk around the neutron star. He has shown that this is independent of the relation between the accretion rate and X-ray intensity of the source. This diagnostic makes use of measurable quantities like the QPO frequency $\nu_{\rm QPO}$ and the change in the spin rate $\dot{\nu}$ of the X-ray pulsar. In the case of slow pulsars like 4U 1907+09, where $\omega_s \ll 1$, the following relation holds:

$$\log \dot{\nu} = \sigma \log \nu_k + {\rm const} \; , \qquad (11)$$

where σ represents the slope of the line describing the relationship between $\dot{\nu}$ and ν_k.

The possible values of σ for various disk models have been derived by Ghosh (1996, 1998). These models include criteria like gas pressure– or radiation pressure–dominated (GPD or RPD) and also one- or two-temperature (1T or 2T) disks. The values of the slope σ for various models are tabulated in Table 3, as adapted from Ghosh (1996, 1998). A determination of the value of σ enables us to discriminate among the four types of disk models that are summarized in Table 3.

As discussed earlier, 4U 1907+09 has shown a constant spin-down rate ($\dot{\nu}$) since its discovery with a maximum variation of 5%. If we assume that the value of $\dot{\nu}$ does not change more than this value during the flaring, we can derive an upper limit for σ of 0.66 at a 90% level of confidence. Comparing this value with those given in Table 3, it can be seen that all the disk models except the two-temperature, optically thin, gas pressure–dominated, Compton low-energy photon model (Shapiro, Lightman, & Eardley 1976) are excluded. This model describes an accretion disk whose inner region is considerably hotter and geometrically thicker. However, the inner region of the disk is optically thin to absorption and is gas pressure–dominated, unlike radiation pressure–dominated models. Under specific boundary conditions, the model yields, from first principle, electron temperatures of 10^9 K and ion temperatures 3–300 times hotter. In the two-temperature inner region of the disk, soft X-ray photons undergo inverse Compton scattering, producing the hard X-ray photons. The spectrum above 8 keV is, therefore, produced by

TABLE 3

DISK MODEL DIAGNOSTICS

Disk Model[a]	Value of σ
1T Optically thick GPD	2.33
1T Optically thick RPD	4.11
2T Optically thin GPD Compton bremsstrahlung	1.06
2T Optically thin GPD Compton low-energy photon	0.06

[a] See Ghosh 1996, 1998 and references therein for model description.

inverse Compton scattering of soft X-ray photons. Thus Comptonization is the dominant cooling mechanism for the disk. It will be possible to test this inference from future wide spectral band observations of 4U 1907+09 with good energy resolution detectors during the flaring state of 4U 1907+09. Such detailed spectral studies may provide further evidences for the presence of such a transient accretion disk and its nature.

5. CONCLUSION

The spin-down rate of the pulsar 4U 1907+09 measured from two IXAE observations separated by two years is 0.23 ± 0.01 s yr^{-1}, which is consistent with the average spin-down rate of this pulsar, indicating that the pulsar has been in monotonic spin-down phase since its discovery. The detection of transient oscillations with a period of 14 s during a secondary flare is the second example of the partial phase occurrence of a transient accretion disk around the neutron star. This observation supports the idea that this is the spin-down mechanism in this pulsar. For a monotonous spin-down of the pulsar, it is required that the transient disk formation occur in a majority of the binary orbits. Application of disk diagnostics to the measured parameters of QPOs suggests that a two-temperature, optically thin, gas pressure–dominated, Comptonized disk model is more likely. Therefore, further observations during the flares, with good spectral resolution and wide-band detectors, may provide evidence for this model.

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