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TEMPORAL ANALYSIS OF EXO 0531−66 IN OUTBURST

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ABSTRACT

We report a timing analysis of the Be transient X-ray binary EXO 053109−6609.2 in outburst observed with *BeppoSAX*. The luminosity of the source is $\sim 1.1 \times 10^{37}$ ergs s^{-1}, similar to that observed in the previous three outbursts. The source shows pulsations from 0.1 up to 60 keV. The pulsed fraction does not seem to decrease with the energy. The pulse profile is double peaked in the whole energy band. The barycentric pulse period is 13.67590 ± 0.00008 s at MJD 50,520.0. The average rate of period change during the ~ 2 days of *BeppoSAX* observation is $(3.7 \pm 0.5) \times 10^{-9}$ s s^{-1}. Comparison with *ROSAT* data allowed the determination of a secular spin-down $\dot{P}_{sec} \sim (3.67 \pm 0.05) \times 10^{-11}$ s s^{-1}, computed over an interval of 1960 days.

Subject headings: stars: individual: EXO 053109−6609.2 — stars: magnetic fields — stars: neutron — X-rays: stars

1. INTRODUCTION

The X-ray source EXO 053109−6609.2 was discovered by *EXOSAT* in deep exposures of the LMC X-4 region (Pietsch, Dennerl, & Rosso 1989). It was seen only for a month (between 1983 October and November) by *EXOSAT*. Adopting a distance consistent with the Large Magellanic Cloud, the derived luminosity between 0.15 and 4 keV is $\sim 6 \times 10^{36}$ ergs s^{-1}. The coded mask X-ray telescope SL2 XRT flown on board the shuttle Challenger between 1985 July and August detected a second outburst (Hanson et al. 1989). The reported luminosity between 2 and 10 keV was $\sim 1 \times 10^{37}$ ergs s^{-1}. The source has been monitored from 1990 June to 1994 July by the *ROSAT* Position Sensitive Proportional Counter (PSPC) (Haberl, Dennerl, & Pietsch 1995). During this period a third outburst was detected from 1993 March to May. The average luminosity between 0.1 and 2.4 keV was $\sim 2.4 \times 10^{36}$ ergs s^{-1}. In the remaining time the source was sometimes detected in a low state with a luminosity $\lesssim 10^{35}$ ergs s^{-1}.

The companion is optically identified with a Be star (Haberl et al. 1995). On 1991 October 31 the source was detected in a moderately high state with a 0.1–2.4 keV luminosity $\sim 5.7 \times 10^{35}$ ergs s^{-1}, a factor of 4 lower than the average luminosity during the outburst of 1993 March. A timing analysis performed on these *ROSAT* data allowed the detection of coherent pulsation with a barycentric pulse period of 13.67133 ± 0.00005 s at 1991 October 31.158 UT. During 3.3 days a rate of period change $(1.5 \pm 0.1) \times 10^{-8}$ s s^{-1} has been reported (Dennerl, Haberl, & Pietsch 1995).

Timing analysis on the pre-*ROSAT* data has not been reported to date.

2. OBSERVATIONS

The *BeppoSAX* satellite (Boella et al. 1997a) observed, with its narrow field instruments, the LMC X-4 region on 1997 March 13 for ~ 2 days. The X-ray binary LMC X-4 was in a low state with a 2–10 keV luminosity $\sim 10^{36}$ ergs s^{-1}, adopting a distance of 55 kpc (by comparison the source luminosity in its high state of 1988 March 7–10 observed with *Ginga* is $\sim 2 \times 10^{38}$ ergs s^{-1}; Woo et al. 1996). The Low Energy Concentrator Spectrometer (LECS; energy range 0.1–10 keV) and the Medium Energy Concentrator Spectrometer (MECS; energy range 1–10 keV) fields of view are 20′ and 30′ in radius, respectively (Parmar et al. 1997; Boella et al. 1997b). The angular separation between LMC X-4 and EXO 053109−6609.2 is $\sim 16'.5$, so EXO 053109−6609.2 was clearly detected in the field of view of both instruments. This source was brighter than LMC X-4: adopting an off-axis reduction of the MECS flux of $\sim 60\%$, appropriate for $16'.5$, its 2–10 keV luminosity was $\sim 1.1 \times 10^{37}$ ergs s^{-1}. In the *ROSAT* range (0.1–2.4 keV) the estimated luminosity was $\sim 2.3 \times 10^{36}$ ergs s^{-1}, almost equal to the luminosity detected by *ROSAT* during the 1993 March outburst. The Phoswich Detection System (PDS; energy range 15–200 keV) on board *BeppoSAX* does not have imaging capabilities (Frontera et al. 1997); its field of view is 78′ (FWHM). So the data include the emission from both LMC X-4 and EXO 053109−6609.2. The LECS, MECS, and PDS light curves are shown in Figure 1. During the whole observation the MECS light curve is quite flat. On timescales ~ 30 s the light curve shows random fluctuations up to a factor ~ 2 (Fig. 1, *inset*). On the contrary, the LECS light curve shows flaring episodes. Most of them are concentrated within ~ 20 ks after 35 ks from the beginning of the observation with flux enhancement events up to a factor of ~ 5 lasting for ~ 3 ks. Two other episodes are present within 10 ks after 120 ks from the beginning. The PDS light curve shows flares similar in relative intensity variations to those observed in the LECS. The first flaring episode is roughly coincident with the LECS event.

3. TEMPORAL ANALYSIS

In order to do a temporal analysis, the arrival times of all the events were reported to the solar system barycenter. The maximum number of photons for both sources are in the MECS data with 5.2×10^{-2} counts s^{-1} and 2.3×10^{-1} counts s^{-1} for LMC X-4 and EXO 053109−6609.2, respectively. So we used these data to find the spin period of both sources. We extracted circular regions in the MECS field of

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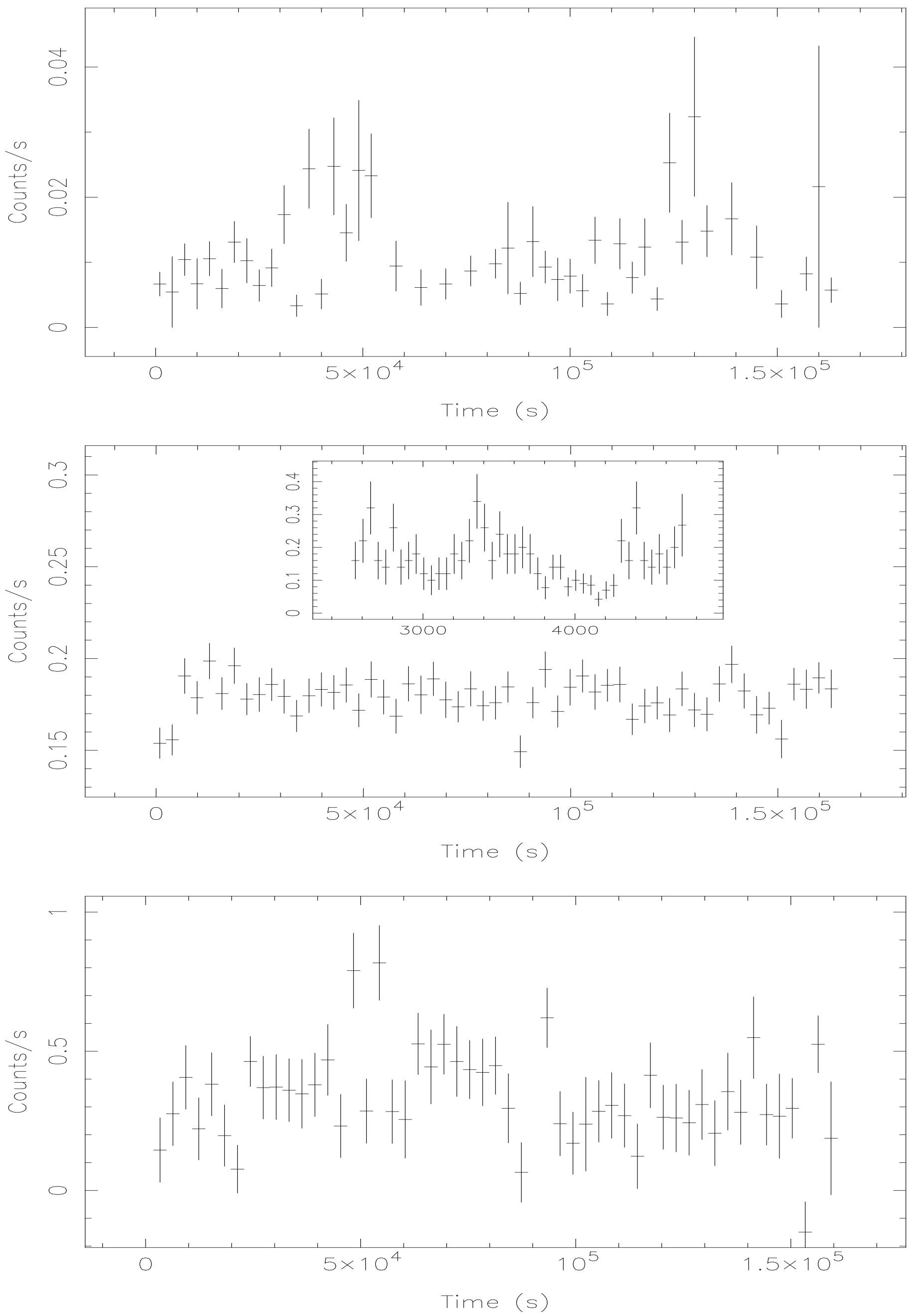

FIG. 1.—Light curves of the *BeppoSAX* observation of EXO 053109−6609.2 in various energy bands. The temporal bin size is 3000 s. *Top panel*: Light curve in the 0.1–1.8 keV band (LECS). *Middle panel*: Light curve in the 1.0–10.5 keV band (MECS). *Inset*: magnification of 2200 s of the MECS light curve binned at 30 s. *Bottom panel*: Light curve in the 15–60 keV band (PDS).

view of 4′ centered on the maximum of the point-spread function of each source. This region is large enough to include more than 95% of the photons detected. We searched for periodicities computing power spectra in the range 2.5×10^{-5} to 3.3 Hz from fast Fourier transforms performed on MECS data of both sources. No pulse periodicities were found in LMC X-4. An example of its power spectrum, centered on the frequency where the periodicity is expected, is shown in Figure 2.

An evident harmonic at $\nu = 0.1465$ Hz was present in the power spectrum of EXO 053109−6609.2. We then performed a folding search for periodicities around the values reported in the literature for LMC X-4 (Woo et al. 1996), and around the value found for EXO 053109−6609.2. No spin modulation was detected in LMC X-4. This is not surprising, because the absence of spin period modulation has been reported during LMC X-4 low states (Kelley et al. 1983). On the contrary, EXO 053109−6609.2 showed a strong χ^2 peak centered at $\bar{P} = 13.67632$ s. We searched for variations of the spin period during the ∼160 ks of *BeppoSAX* observation. To this end we divided the whole data set into 14 overlapping intervals of 40 ks. The start times of these intervals were separated by 10 ks. A folding search around $\bar{P}$ was performed in each interval. Each interval contained ∼3000 pulses, enough to guarantee that the peak of the χ^2 curve is clearly defined and not deformed by the statistical fluctuations. The corresponding best periods were obtained fitting the χ^2 peak with a Gaussian. A plot of

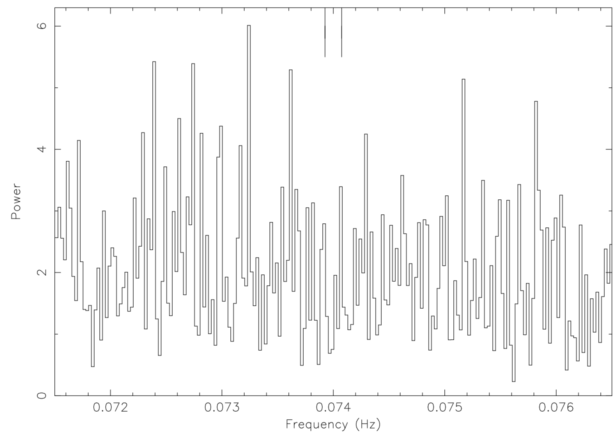

FIG. 2.—Power spectrum (PSD) of LMC X-4 obtained from MECS data (1.0–10.5 keV energy band) extracted from a circular region of 4′ radius centered on the source. Four PSDs, computed from time intervals of length ~40 ks, were averaged. The bin size is 0.1525 s. The two lines limit the frequency range in which the LMC X-4 periodicity is expected, taking into account the secular period derivative and the period derivative induced by the orbital motion. The parameters for the LMC X-4 system were taken from Woo et al. (1996). The PSD is normalized according to Leahy convention (Leahy et al. 1983).

these periods versus time is shown in Figure 3. This figure shows fluctuations of the spin period around a gross spin-down trend. We performed a linear fit to derive the average first derivative of the period. We found $P(T_0) = 13.67590 \pm 0.00008$ s, $\dot{P}_{\rm trend} = (3.7 \pm 0.5) \times 10^{-9}$ s s^{-1}, $T_0 =$ MJD 50,520.0. In order to test the significance of our result, we computed $\dot{P}_{\rm trend}$ adopting an independent method: we cross-correlated an average template pulse profile with those obtained from consecutive intervals of 13 ks each. Performing a timing analysis on the temporal delays, we obtained a first period derivative within the errors of the previous one (Di Salvo 1997). Adopting the value for the period derivative reported above, we folded the LECS, MECS, and PDS light curves. The pulse profiles in different energy bands as well as some hardness ratios are shown in Figures 4 and 5.

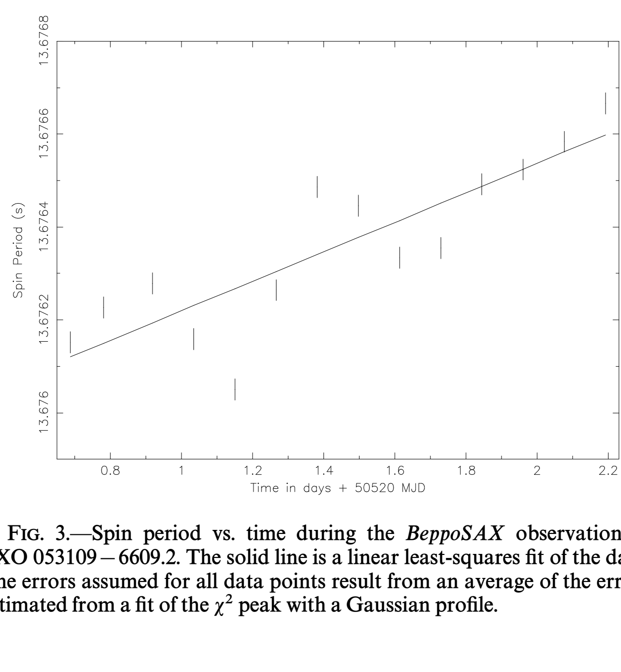

FIG. 3.—Spin period vs. time during the *BeppoSAX* observation of EXO 053109 − 6609.2. The solid line is a linear least-squares fit of the data. The errors assumed for all data points result from an average of the errors estimated from a fit of the χ^2 peak with a Gaussian profile.

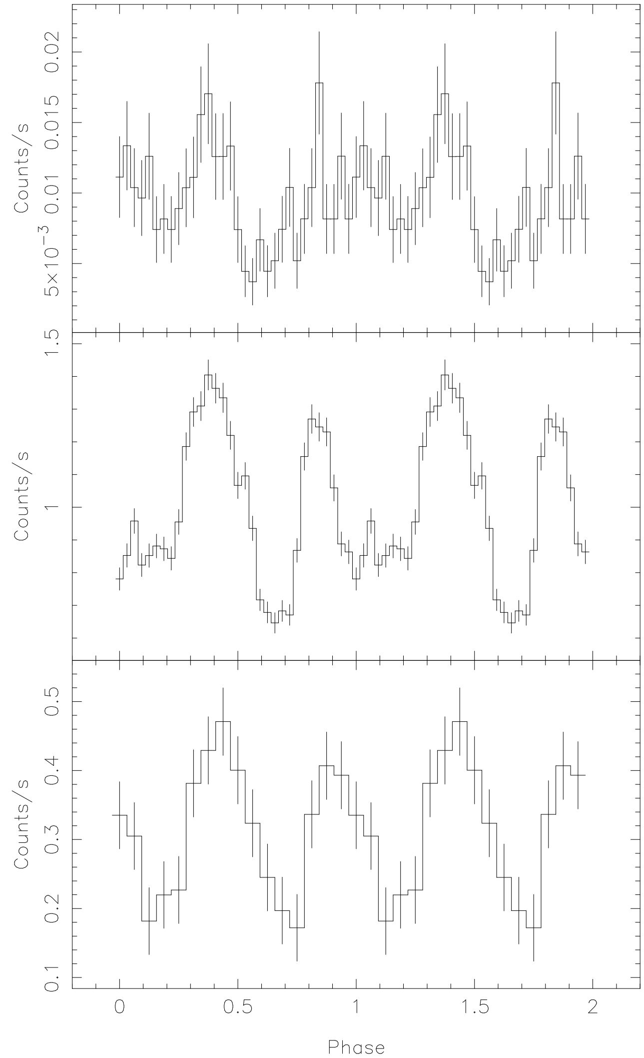

FIG. 4.—Pulse profiles in various energy bands. The folding is performed adopting the period derivative found from the linear fit of the points of Fig. 3. *Top panel*: 0.1–1.8 keV band (LECS). *Middle panel*: 1.8–10.5 keV band (MECS). *Bottom panel*: 15.0–60.0 keV band (PDS).

4. DISCUSSION

We computed the secular spin derivative of EXO 053109 − 6609.2 from the spin period given by Dennerl et al. (1995) at 1991 October 31.158 UT and our estimate at 1997 March 13.0 UT. We found $\dot{P}_{\rm sec} = (3.67 \pm 0.05) \times 10^{-11}$ s s^{-1}. This value is 2 orders of magnitude less than the derivative found from the fit of *BeppoSAX* data.

Given the fact that the source during the *BeppoSAX* observation was in outburst, significant spin-down episodes are difficult to reconcile with the inferred high accretion rates. Indeed, the transient Be X-ray pulsars typically show spin-up during their high-luminosity states (Nagase 1989). So we interpreted $\dot{P}_{\rm trend}$ as resulting from a probable intrinsic spin-up (caused by the high accretion rate) Doppler shifted to the observed spin-down by an orbital motion. Superimposed on $\dot{P}_{\rm trend}$, fluctuations are present that cannot be ascribed to any orbital Doppler effect. We tried to interpret these short-term fluctuations of spin period as caused by variations of the torque exerted by the accreting matter. In the case of a wind-fed system the torques are typically much smaller than those observed, suggesting that the system is accreting from a disk (e.g., Nagase et al. 1984).

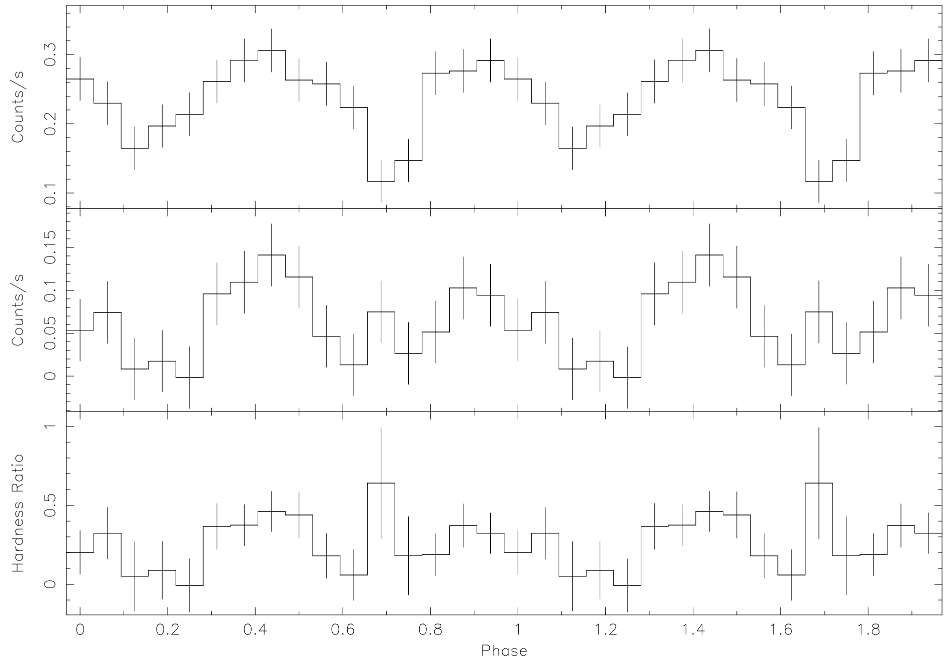

FIG. 5.—*Top panel*: Pulse profile in the 15.0–30.0 keV band (PDS). *Middle panel*: Pulse profile in the 30.0–60.0 keV band (PDS). *Bottom panel*: Hardness ratio (30.0–60.0 keV)/(15.0–30.0 keV).

Indeed, the high luminosity estimated in this observation, $\sim 10^{37}$ ergs s^{-1}, is not consistent with typical values of wind-fed systems with OB companions that tend to have luminosities lower than $\sim 10^{36}$ ergs s^{-1} (White, Nagase, & Parmar 1995). This is in line with the current view that transient Be systems accrete from a dense equatorial wind often expelled by the companion. In this case the formation of a temporary accretion disk takes place once the neutron star is passing close to the periastron (see, e.g., Nagase 1989).

In the case of disk accretion, in the hypothesis that the accretion torques are of the order of the accretion rate times the Keplerian specific angular momentum at the accretion radius r_a (see, e.g., Wang 1996), an expression for $\dot{P}$ can be derived:

$$\dot{P} = -1.38 \times 10^{-12} f(\omega_s) m^{-1/2} P^2 I_{45}^{-1} L_{37} \epsilon^{-1} R_6 r_8^{1/2} \text{ s s}^{-1} , \qquad (1)$$

where $f(\omega_s)$ is the dimensionless torque function, a factor expressing the strength of the torque and quoted by various authors to be of the order of unity (see, e.g., Wang 1996), $\omega_s = P_K(r_a)/P$ is the fastness parameter, $P_K(r_a)$ is the Keplerian period at the accretion radius, m is the neutron star mass in units of $M_\odot$, I_{45} is the neutron star moment of inertia in units of 10^{45} g cm^2, L_{37} is the luminosity in units of 10^{37} ergs s^{-1}, ϵ is the ratio between the observed luminosity and the total gravitational potential energy released per second by the accreting matter, R_6 is the neutron star radius in units of 10^6 cm, and r_8 is the accretion radius in units of 10^8 cm. The accretion radius is ϕ times the Alfvén radius R_A (see, e.g., Hayakawa 1985):

$$R_A = 4.3 \times 10^8 \mu_{30}^{4/7} R_6^{-2/7} L_{37}^{-2/7} \epsilon^{2/7} m^{1/7} \text{ cm} , \qquad (2)$$

where μ_{30} is the magnetic moment in units of 10^{30} G cm^3. Adopting the standard α-disk equations (Shakura & Sunyaev 1973) and assuming that the thickness of the transition region at the magnetosphere is $\ll r_a$, we found

$$\phi = 0.31 \alpha^{9/35} L_{37}^{3/70} \epsilon^{-3/70} m^{-1/140} R_6^{3/70} r_8^{-3/28} , \qquad (3)$$

where α is the Shakura-Sunyaev parameterization for the viscosity coefficient. As is possible to observe, ϕ depends weakly on all the parameters and is in line with the value 0.5 derived by some authors (Ghosh & Lamb 1991).

More recently, Wang (1997) has studied the torque exerted on an oblique rotator by a magnetically threaded accretion disk. He concluded that ϕ increases as the inclination angle χ between the magnetic moment and the spin axis (assumed normal to the disk plane) decreases. Indeed, his estimates give $\phi \sim 1$ for all inclinations.

For typical values of the neutron star radius, mass, and magnetic moment and for the observed luminosity of EXO 053109−6609.2, $\sim 10^{37}$ ergs s^{-1}, equations (1)–(3) give $\dot{P} \sim 3 \times 10^{-10} f(\omega_s)$ s s^{-1}. $\dot{P} \sim 6 \times 10^{-10}$ s s^{-1} for $f(\omega_s) \sim 2$, which is reasonable for spin periods far from the instantaneous equilibrium (Wang 1996), as is the case if during outbursting episodes the inner edge of the accretion disk is pushed inward in the magnetosphere. This is marginally consistent with the fluctuations observed that are $\dot{P}_{\rm fluct} \sim 6 \times 10^{-9}$ s s^{-1}. It is worth noting that the first spin-up episode observed after ~ 1.15 days from the beginning of the observation is roughly coincident with the first flaring episode observed in the LECS and PDS light curves. However, the flux data are not of sufficient quality to allow us to unambiguously demonstrate this correlation.

Information about the emission region can be derived by an analysis of the pulse profiles in different energy bands. The MECS pulse profile in the 1.8–10.5 keV band (Fig. 4, *middle panel*) shows a double-peaked pulse profile. The two peaks are $\sim 180°$ apart. The main pulse is $\sim 20\%$ higher than the interpulse. The pulsed fraction (pf) defined as $(I_{\rm max} - I_{\rm min})/I_{\rm max}$, where $I_{\rm max}$ and $I_{\rm min}$ are respectively the maximum and minimum intensity in the folded pulse profile, is 0.54 ± 0.05. In the LECS pulse profile (the 0.1–1.8 keV band; Fig. 4, *top panel*), the main pulse is still evident, while the interpulse is more broadened, and pf = 0.78 ± 0.28. The PDS pulse profile (15–60 keV energy band; Fig. 4, *bottom panel*) still shows a double-peaked structure (pf = 0.64 ± 0.16) in phase with the previous ones. Although the statistics is poor, the pulsed fraction does not seem to decrease with energy (see Fig. 6). To better investigate this, we plotted in Figure 5 the PDS pulse profiles in the 15–30 and 30–60 keV energy bands and the relative hardness ratio. The source shows pulsations above 30 keV. For energies greater than 60 keV EXO 053109−6609.2 is still visible, but the statistics is too poor to allow the detection of any pulsed component.

Therefore, EXO 053109−6609.2 shows a hard tail (above 30 keV) strongly modulated at the spin period. This seems to indicate that this tail originates not too far from the neutron star surface. For the estimated 2–10 keV luminosity of $\sim 10^{37}$ ergs s^{-1}, theoretical models predict that the emission regions on the neutron star surface have the shape of short slabs at the magnetic poles, where the accreting plasma is stopped primarily by Coulomb collisions; a pencil emission is expected for these regimes (Mészáros et al. 1983). Moreover, for luminosities $\sim 10^{37}$ ergs s^{-1} a 180° phase reversal in the pulse profile is expected near the cyclotron resonance frequency (as in the case of 4U 1626−673) (Nagel 1981). No phase shift in the pulse profile is present for EXO 053109−6609.2 up to 60 keV. This supports the idea that the magnetic field is quite strong. A further indication of the presence of a strong magnetic field comes from the spectrum. A detailed analysis of the spectral properties of EXO 053109−6609.2 is beyond the scope of this work and will be presented elsewhere; here we mention the fact that in the energy range 20.0–100.0 keV (PDS) the spectrum is well described by a power law (photon index ∼1.1) modified by an exponential cutoff (cutoff energy $E_{cut} \sim 27$ keV).

Makishima & Mihara (1992) found an empirical although controversial relation between the cyclotron line energy E_{cyc} and the cutoff energy: $E_{cyc} \sim 2 \times E_{cut}$. Adopting this relation, we found $E_{cyc} \sim 60$ keV. From the relation between the magnetic moment strength and the cyclotron line energy E_{cyc} (White et al. 1995), taking into account the gravitational redshift close to the neutron star surface, $\mu_{30} = 0.086(E_{cyc}/1\ \mathrm{keV})R_6^{-3}(1 - 0.30mR_6^{-1})^{-1/2}$, a lower limit for the magnetic moment can be derived: $\mu_{30} > 6.8$. This would reduce the discrepancy between the theoretical and the observed spin fluctuations to a factor of less than 6.

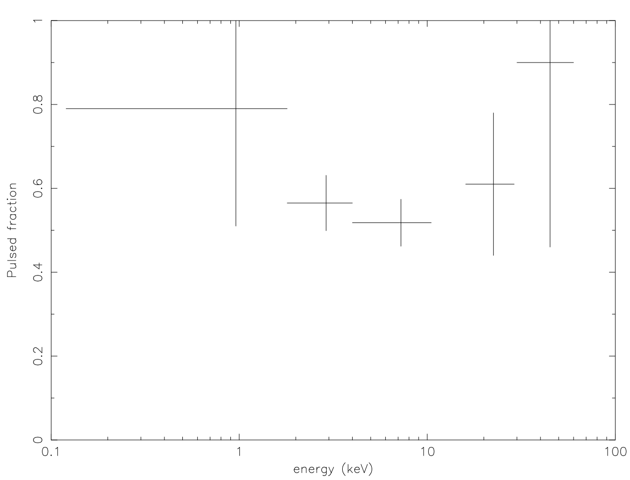

FIG. 6.—Pulsed fraction vs. energy

Finally, we want to observe that the high-intensity state observed by *ROSAT* in 1991 October and the outburst observed by *BeppoSAX* in 1997 March occurred ∼2922 and ∼4920 days after the first outburst observed by *EXOSAT* in 1983 October. These two points are compatible with a long binary orbital period between 600 and 700 days, as previously noted by Haberl et al. (1995), if the outbursts are related to the periastron passage of the neutron star. In particular, the intervals of the four outburst episodes from the first (1983 March) are ∼640 days (SL2 XRT; 1985), ∼2922 days (*ROSAT*; 1991), ∼3460 days (*ROSAT*; 1993), and ∼4920 days (*BeppoSAX*; 1997). All these values are compatible (within 15%) with an orbital period of ∼700 days. Encouragingly, outburst durations ∼15% of the binary period are expected for eccentricities $\gtrsim$0.4–0.5, typical of this kind of system.

This long orbital period is unusual for Be X-ray binaries; however, the system PSR B1259−63 (Johnston et al. 1994) contains a 3.3×10^{11} G neutron star in a highly eccentric orbit of 1236.79 days around a Be companion. This suggests that long orbital periods for systems of this kind are not unreasonable. On the other hand, Dennerl et al. (1996) performed a detailed analysis on *ROSAT* data spanning more than 4 years. They assumed that the spin-down observed in the longest *ROSAT* observation (∼3.3 days) is entirely due to an orbital motion. With this they were able to constrain the orbital period in the range 4–70 days for eccentricities $\lesssim$0.3. This suggestion is compelling. However, the assumption that the spin period derivative exclusively reflects the orbital motion (and is unbiased, e.g., by a spin-up effect expected during high accretion episodes) is questionable. Indeed the secular spin-up of A0535+26 is comparable in magnitude to the spin derivative observed in EXO 053109−6609.2 (White et al. 1995). So significant period derivative contamination from effects other than orbital cannot be excluded.

5. CONCLUSION

We reported the detection by *BeppoSAX* of an outburst of the Be transient binary EXO 053109−6609.2. The 2–10 keV luminosity ($\sim 1.1 \times 10^{37}$ ergs s^{-1}) is comparable to the luminosity reported in the other three outbursts detected up to now. Luminosity fluctuations up to a factor of 5 on timescales ∼3 ks were present both in the low-energy (LECS 0.1–1.8 keV) and in the high-energy (PDS 15–60 keV) bands, while the luminosity was more stable in the medium-energy band (MECS 1.0–10.5 keV). The spin period fluctuates around a general spin-down trend ($\dot{P}_{trend} \sim 4 \times 10^{-9}$ s s^{-1}) probably due to Doppler effect induced by orbital motion, although contamination effects from a simultaneous intrinsic spin-up behavior, induced by the high accretion rate, seem probable. The secular period derivative, obtained comparing the spin period determined during this observation with the spin period determined during a *ROSAT* observation ∼5.5 years ago, is $\dot{P}_{sec} \sim 4 \times 10^{-11}$ s s^{-1}, 2 orders of magnitude less than the local trend. The short-term fluctuations of the spin period ($|\dot{P}_{fluct}| \sim 6 \times 10^{-9}$ s s^{-1}) are only barely consistent with the theoretical predictions of spin fluctuations induced by accretion torque variations (a factor of 10 smaller for this range of luminosity). A correlation is probably present between the first spin-up episode and the first group of small luminosity flares observed in the LECS and PDS light curves. The pulse profile in different energy bands shows a double-peaked structure with the two peaks $\sim 180°$ apart. A pulsed component is clearly detectable up to 60 keV. No significant variation in the pulse shape or phase is visible up to 60 keV.

Allowing for some caution due to the poor statistics, the pulsed fraction is about constant in the whole energy range. All the outburst episodes observed up to now are compatible with an orbital period of ~ 700 days, with a duty cycle of $\sim 15\%$ implying a moderately eccentric orbit, typical of this kind of system. Alternatively, the question remains to be addressed whether the occurrence of this outburst is compatible with the shorter orbital periods in the range 4–70 days recently proposed for this source.

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