LONG-TERM FREQUENCY HISTORY OF THE BE/X-BINARY SYSTEM SAX J2103.5+4545

A. Camero Arranz[1], C. A. Wilson[2], M. H. Finger[3], and V. Reglero[4]

[1] *GACE, ICMUV, Univ. de Valencia,P.O. Box 20085, 46071 Valencia, Spain, E-mail: Ascension.Camero@uv.es*
[2] *XD12 NASA Marshall Space Flight Center, Huntsville,AL 35812,USA, E-mail:Colleen.Wilson-Hodge@msfc.nasa.gov*
[3] *XD12 NASA Marshall Space Flight Center, Huntsville, AL 35812, USA, E-mail:Mark.Finger@msfc.nasa.gov*
[4] *GACE, ICMUV, Univ. de Valencia,P.O. Box 20085, 46071 Valencia, Spain, E-mail: Victor.Reglero@uv.es*

ABSTRACT

We have carried out a long-term pulse-timing analysis of the transient X-ray pulsar SAX J2103.5+4545 using data from the *INTEGRAL* and the *RXTE* missions. We present the long-term flux, frequency, and spin-up rate histories. An analysis of the correlation between the flux and spin-up rate is also shown and a hardness ratio study in included. Finally, we have determined a new set of orbital parameters. The new orbital period obtained is P_{orb}= 12.66582±0.00077 days.

Key words: BeX stars; HMXRBs; SAX J2103.5+4545
.

1. INTRODUCTION

SAX J2103.5+4545 was discovered by *BeppoSAX* satellite ([1]) in 1998. This transient X–ray system is a Be High Mass X-ray Binary (HMXRB) pulsar with an orbital period ∼12.68 d and X-ray pulsations of ∼358 s. The likely optical counterpart is a B0Ve star (V = 14.2) at a distance of 6.5 kpc ([2]). Using *XMM-Newton* data a quasi-periodic oscillation at 22.7 s was discovered by [3]. In 2002, [4] found a correlation between spin-up rate and X–ray flux during the 1999 outburst. This suggests the formation of an accretion disk during periastron passage of the neutron star. However, SAX J2103.5+4545 doesn't follow the Corbet correlation P_{orb} vs P_{spin} found in other accreting pulsar systems. Previous *INTEGRAL* analysis of this source have been carried by [5] , [6] , [7], [8], and [9]. We present long-term pulse-timing analysis of SAX J2103.5+4545 using data from both the *INTEGRAL* and the *RXTE* missions.

2. OBSERVATIONS AND DATA REDUCTION

SAX J2103.5+4545 has been detected by IBIS/ISGRI during *INTEGRAL* PV phase and the GPS survey from 2002 to 2005 (MJD 52618 – MJD 53356), with a total observing time of ∼860 ks. *INTEGRAL* data reduction was carried out with ISDC's ([10]) Offline Scientific Analysis software, release 5.0. A software description can be found in [11], [12] , and [13]. This source was also observed with the *RXTE* Proportional Counter Array (PCA;[14]) [1] from 1999 to 2004 (MJD 51512.8 – MJD 53047.9), with a total observing time of ∼1900 ks. For each observation, we have analyzed PCA Standard1 data for the light curves and Standard2 data for spectral analysis, using FTOOLs V6.0.5.

3. RESULTS

3.1. Long-term pulse-timing analysis

We obtained either a list of good events times per science window (ScW) (*INTEGRAL* IBIS/ISGRI, 20-60 keV band) or binned light curves (*RXTE* PCA, 2-60 keV). Then, we corrected the times to the barycenter of the solar system, as well as for the orbital motion using the binary orbital parameters by [4]. We constructed pulse profiles by fitting the data with a harmonic expansion in pulse phase. To do that we estimated a preliminary simple phase model ($\phi(t_k)= \phi_o+f_o(t_k-t_o)$; where f_o is the pulse frequency at time t_o and ϕ_o is the phase at time t_o). For the *RXTE* PCA observations we collected 4000 s pulse profiles (∼11 pulse periods) created in a 12.69 d interval to avoid contamination of the orbital motion. Finally, a grid search in frequency and frequency derivative was carried out. For the *INTEGRAL* IBIS/ISGRI data the approach was different, due to the non continuous observational pattern and the sensitivity of the ISGRI detector. In table 1 we show a summary of the detections and non detections with this instrument, as well as the number of ScW's used for making profiles. A template profile was then created from the average profile from the set of ISGRI ScW's and from the collected pulse profiles from the *RXTE* PCA data (see Fig. 1). To generate phase offsets from the model, we then cross-correlated the individual

[1] See http://heasarc.gsfc.nasa.gov/ for observation details

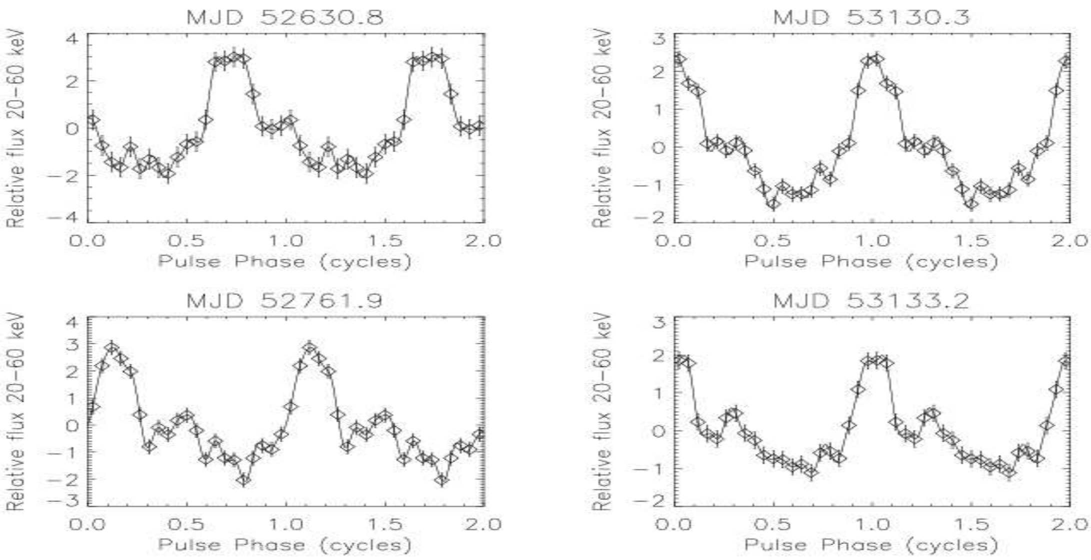

Figure 1. ISGRI (20-60 keV) mean pulse profiles of SAX J2103.5+4545 generated by combining profiles from individual INTEGRAL *ScWs. Different shapes can be clearly seen, which are evidences for temporal variability.*

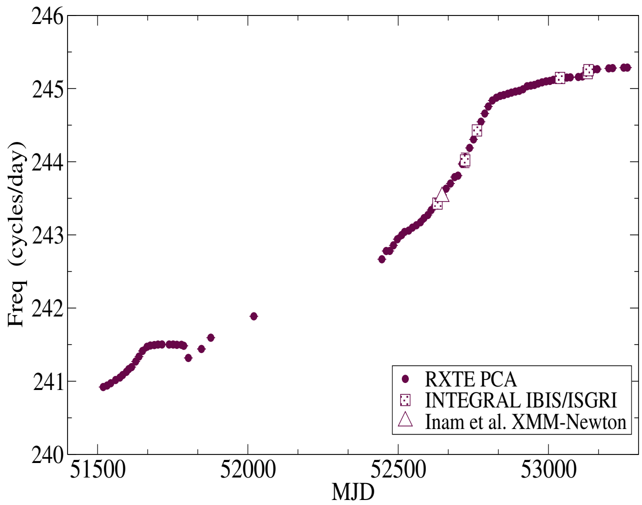

Figure 2. Long-term frequency history (from 1999 to 2005). Data from INTEGRAL *and* RXTE *satellites are shown together.*

profiles with the template profile. The new phases (model + offset) were then fitted with a quadratic phase model, and the process was repeated. Fig 2 shows the long-term frequency and frequency derivative history obtained. The spin rates were computed by differencing adjacent frequency measurements and dividing by the corresponding time difference (Fig. 3).

4. ORBIT FITTING

We have obtained a new data set of orbital parameters in order to achieve a better characterization of the geome-

Table 1. Detections with IBIS/ISGRI.

Epoch (MJD)	number of ScW	Pulse Period (s)
52619.299	6	–
52630.755	49	354.927 ±0.014
52637.303	18	–
52722.884	3	354.072±0.014
52761.947	35	353.478±0.017
52797.040	2	–
52805.978	3	–
52820.945	2	–
53021.331	74	–
53038.548	119	352.446±0.019
53041.996	21	–
53102.514	3	–
53130.288	77	352.350±0.006
53133.176	51	352.29±0.01
53188.993	2	–
53258.517	3	–
53333.056	6	–
53349.280	5	–
53354.965	4	–

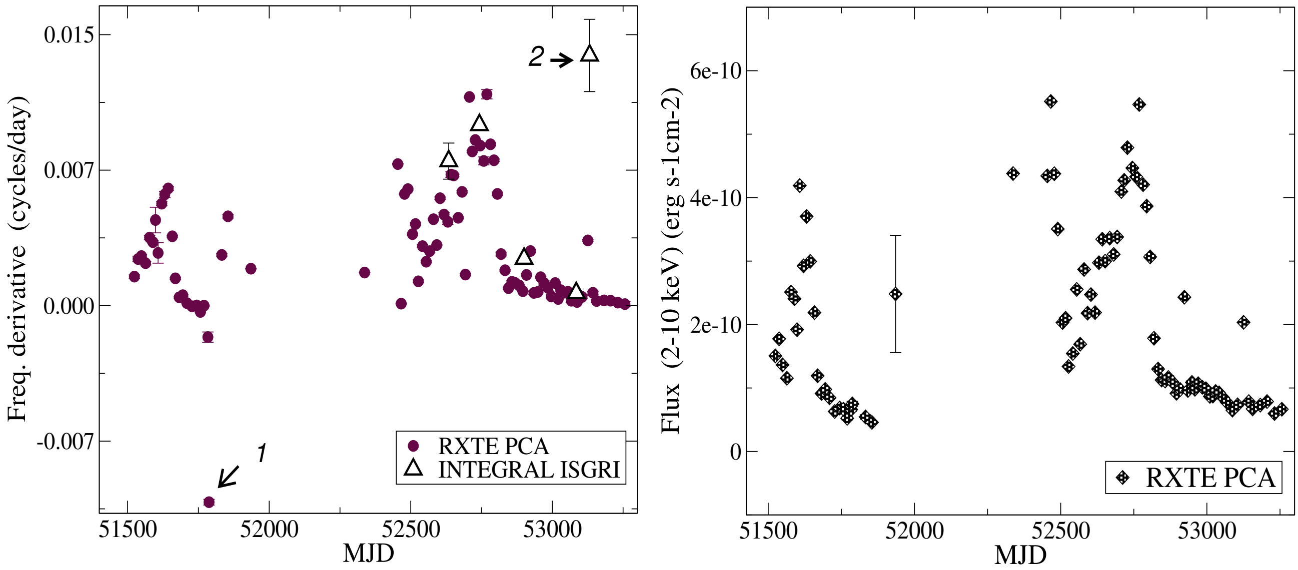

Figure 3. Left. Spin rates. Two points are clear outliers. The labeled number 1 we suspect may not be a reliable detection. However, we believe that number 2 is real when comparing the fluxes obtained in the light curve. Right. The 2-10 keV RXTE *PCA fluxes. A spin-up rate and X–ray flux correlation was found, confirming that an accretion disk during periastron passage is present.*

Table 2. Orbital solution for SAX J2103.5+4545.

	Present work	Baykal et al. (2002)	İnam et al. (2004)	Sidoli et al. (2005)
$T_{pi/2}$ (MJD)	52494.80±0.03	51519.3±0.2	52633.90±0.05	
P_{orb} (days)	12.66582±0.00077	12.68±0.25		12.670±0.005
$a_x \sin i$ (lt-s)	80.7±0.6	72±6		
e	0.403±0.017	0.4±0.2		
ω	240.14±2.5	240±30		

try of this binary system. On the other hand, errors in the orbital parameters caused by coupling between the intrinsic spin variations of the pulsar with orbital effects, can scatter the detected pulse frequencies. Thus we split the *RXTE* results into 29 intervals and fit an orbit to each one separately (the orbital Period was fixed). The fitting model for each interval consisted of a global orbit, a quadratic-phase model for the *RXTE* PCA data. We also accounted for additional aperiodic noise (for more details see [15] and [16]). Table 2 lists the best-fit orbital parameters obtained for the combined fit, where $T_{pi/2}$ is the epoch when the mean orbital longitude is equal to 90 deg, P_{orb} is the orbital period, $a_x \sin i/c$ is the light-travel time for the projected semi-major axis (i is the inclination angle), e is the eccentricity and ω is the longitude of periastron.

5. DISCUSSION

First studies by [4] showed a transition from spin-up to spin-down in the *RXTE* observations from an outburst in November 1999, suggesting the presence of an accretion disk. The detection of a quasi-periodic oscillation at 22.7 s discovered by [3] in 2004 provided further evidence for this. Fig. 2 shows that the first outburst of SAX J2103.5+4545 started with a spin-up trend , made a transition to a steady spin rate, and then appeared to just begin a spin-down trend. The following available data started with a quick spin-up trend, and then a transition to a slower spin-up rate. Fig. 3 shows that the spin-up rate and X-ray flux correlation is also observed, confirming that an accretion disk is present during periastron passage. In this figure, two points are clear outliers. Most likely the labeled number 1 may not be a reliable detection. However, we believe that number 2 is real. Comparing the fluxes obtained in the non averaged long–term light curve, that is, the one composed of around 500 individual flux measurements from the spectra, we real-

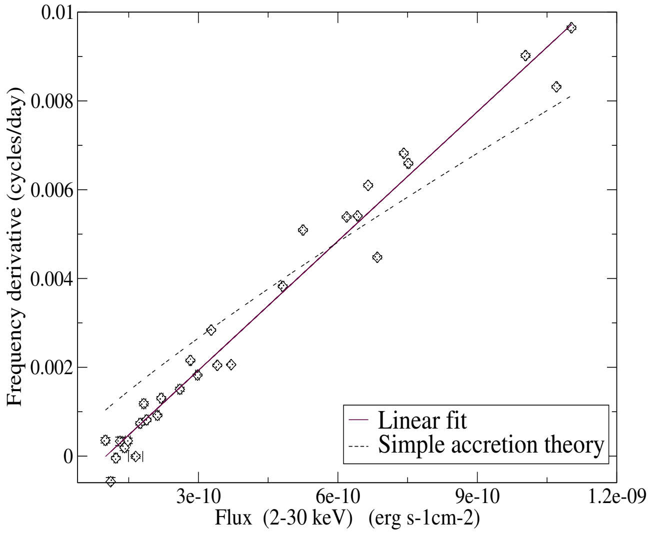

Figure 4. Average spin-up rates vs. RXTE *PCA (2-30 keV) non absorbed fluxes. A correlation coefficient of 0.9734 and chance of probability of 8.215e-19 were found.*

ized that while SAX J2103.5+4545 was in the faint state around MJD 53100 (outlier number 2), suddenly it increased dramatically its luminosity for a very short time period. This was not the first episode of these characteristics we found during the second observed faint state but the strongest one. Therefore, outlier number 1 could be ruled out since it seems it is not related to any significant event. On the contrary, outlier number 2 is probably real as we already discussed.

In Fig. 4 we have also shown two different fits to the Flux vs. frequency derivative relation : a linear fit and a power-law fit with an index of 6/7 predicted from simple accretion theory. We can see that the second fit does not match totally the observed behavior. It suggests that a more sophisticated model, e.g. Gosh and Lamb ([17]) may be needed at low-flux end because the pulsar is beginning to spin-down. At the high-energy flux end, beaming may be boosting the observed flux, or there may be considerable emission outside the 2–30 keV range. In Fig. 2 we can see that the spin rates computed using our improved orbital model follows nicely the averaged light curve from the extracted PCA spectra. In order to study the spectral variability of SAX J2103.5+4545 we have compute the long-term hardness ratios history using two energy bands: 2–30 keV and 2–10 keV (defined as $HR = H/S$). Fig. 5 shows that the source becomes harder when the flux is higher. These fluxes were obtained by fitting a cut-off power law model plus a photoelectric absorption to each of the 548 spectra, fixing the iron line value and its width to 6.43 keV and 0.165, respectively ([4]). The *XMM-Newton* value from [3] is in good agreement with our results. In general, either the pulse period estimations from [7] or those ones from [18] are not in very good agreement with our results. However, the uncertainties are large in the first case.

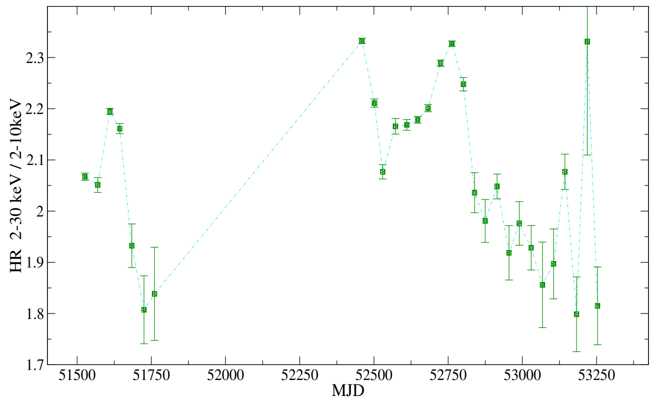

Figure 5. Long-term hardness ratios history. SAX J2103.5+4545 becomes harder when the flux is higher.

REFERENCES

[1] Hulleman, F., in 't Zand, J. J. M., Heise,J., 1998, *A&A*, 337L, 25H

[2] Reig, P., Negueruela, I., Fabregat, J., et al. 2004, *A&A*, 421, 673

[3] İnam, S. ., Baykal, A., Swank, J., Stark, M. J., 2004, *ApJ*, 616, 463I

[4] Baykal, A., Stark, M. J., Swank, J. H., 2002, *ApJ*, 569, 903B

[5] Lutovinov, A. A., Molkov, S. V., Revnivtsev, M. G., 2003, *ASTL*, 29, 713L

[6] Sidoli, L., Mereghetti, S., Larsson, S., Chernyakova, M.,2004, Proc. 5th *INTEGRAL* Workshop (*ESA SP-552*), 475

[7] Sidoli, L., Mereghetti, S., Larsson, S., Chernyakova, M., 2005, *A&A*, 440, 1033S

[8] Blay, P., Reig, P., Martínez Núñez, S., Camero, A., 2004, *A&A*, 427,293B

[9] Falanga, M., di Salvo, T., Burderi, L., Bonnet-Bidaud, J. M., 2005, *A&A*, 436, 313F

[10] Courvoisier, T. J.-L., Walter, R., Beckmann, V., et al. 2003, *A&A*, 411L, 53

[11] Goldwurm, A., David, P., Foschini, L., et al. 2003, *A&A*, 411L, 223G

[12] Diehl, R., Baby, N., Beckmann, V., et al. 2003, *A&A*, 411L, 117D

[13] Westergaard, N. J., Kretschmar, P., Oxborrow, C. A., et al. 2003, *A&A*, 411L, 257W

[14] Jahoda, K., Swank, J., Giles, A.B. et al. 1996, Proc. *SPIE*, 2808, 59

[15] Finger, M.H., Bildsten, L., Chakrabarty, D., et. al. 1999, *ApJ*, 517, 449F

[16] Buccheri, R., Bennett, K., Bignami, G. F., et al. 1983, *A&A*,128, 245

[17] Wilson, C.A., Finger, M.H., Coe, M.J., Laycock, S., & Fabregat, J. 2002, *ApJ*, 570, 287

[18] Blay, P., Negueruela, I., Reig, P. et al., 2006, in these proceedings.