WIDE-BAND STUDY OF X-RAY PULSARS WITH SUZAKU

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ABSTRACT

A summary is given on the timing accuracy verifications of the Hard X-ray Detector (HXD) on board the *Suzaku* satellite. *Suzaku* has so far observed several X-ray pulsars, such as the Crab pulsar, PSR 1509-58, and A0535+26, partially for the purpose of calibrating the HXD timing accuracy and energy responses. Through standard barycentric corrections and temperature compensations of the oscilator in the central data processing unit, the relative and absolute timing accuracies were confirmed using the HXD data of the Crab pulsar. Some initial *Suzaku* results on X-ray pulsars are also presented.

Key words: *Suzaku*, HXD, Crab pulsar, PSR1509-58, A0535+26,.

1. THE TIMING ACCURACY REQUIREMENTS FOR HXD

The fifth Japanese X-ray satellite *Suzaku* [1] was launched on 2005 July 10, into an orbit about 570 km above the Earth. Carrying onboard the XIS (X-ray Imaging Spectrometer) [2] and the HXD (Hard X-ray Detector) [3] [4], *Suzaku* allows high-sensitivity (down to $\sim 10^{-5}\mathrm{counts\ s^{-1}cm^{-2}keV^{-1}}$) studies of X-ray pulsars over a wide energy band (0.4-600 keV).

The HXD consists of two types of detectors covering different energy ranges. One is semiconductor part (HXD-PIN;10-70 keV) and the other is scintillator part (HXD-GSO;30-600 keV). Both are designed to have a 61 μs

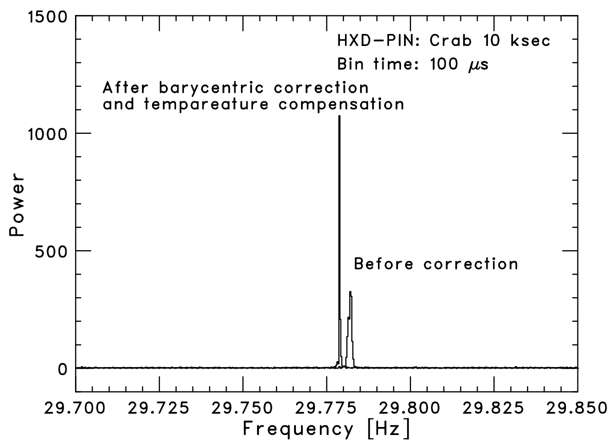

Figure 1. Power Spectra of the Crab pulsar obtained with HXD-PIN before and after the barycentric and temperature corrections (2005/9/15, 10.5 ksec exposure). After these corrections, the best-estimated pulse period is obtained as $P = 33.58088 \pm 0.00001$ msec.

time resolution, whereas the *Suzaku* spacecraft has 100 μs relative and absolute timing acuuracies. All the timing information of *Suzaku*, including that of the HXD, originates from one crystal oscilator in the central data processing unit (DP). The clock frequency is corrected for its temperature-dependent drift on ground, based on the temperature information. The DP clock has a gross stability of the order of 10^{-8} s s^{-1}, which improves to $\sim 10^{-9}$ s s^{-1} through the temperature compensation (§ 2)

In order to verify the in-orbit timing accuracy of the HXD, we used well known pulsars such as the Crab pulsar (~ 33 msec period) and PSR 1509-58 (~ 150 msec period).

2. THE HXD TIMING CALIBRATION USING THE CRAB PULSAR

We analyzed the HXD data of the Crab Nebula, obtained in 2005 August-September on 25 occasions and in 2006 March-April on 3 occasions. After standard barycentric corrections, and temperature compensation of the oscilator in the DP, the pulsations were detected successfully in each observation (Fig1). For example, the barycentric pulse period measured on 2005 September 15 in a 10.5 ksec exposure was 33.58088 ± 0.00001 msec. This value agrees with a near simultaneous radio measurement within a relative accuraacy of 10^{-6}.

Needless to say, the barycentric correction takes into account not only the motion of the Earth around the solar system barycenter, but also that of the spacecraft around the Earth. The formar and the latter Doppler effects causes the pulse period to change, at the worst case, by 1×10^{-4} (± 3 μsec) and 2×10^{-5} (± 0.8 μsec), respectively. If expressed in terms of cumulative jitters in the pulse arrival times, the latter effect amounts to at most ± 20 msec per spacecraft orbit (100 min), which is almost comparable to one full cycle of the Crab pulsar. This effect is cleary seen in Fig1.

The intrinsic pulse period increase of the Crab pulsar was determined from the above span as $\dot{P} = 4.2 \times 10^{-13}$ s s^{-1}. This period change rate is also in a good agreement with past measurements [5] (Fig.2:Top). In order to compare this period increase to that of the radio observations, we plot in Fig.2 (Bottom) the period history derived with the HXD for 2005 August-September, together with the prediction from monthly observations with the Jodrell Bank radio telescope [7]. Based on the good agreement, we conclude that the HXD has a high relative timing accuracy as designed.

To verify the absolute timing accuracy of the HXD, we compared the main pulse peak phase of the Crab pulsar between *Suzaku* and the Jodrell Bank radio telescope. Figure 3 shows the folded pulse profiles of the Crab pulsar, measured on 2005 September 15. There, we folded the HXD data in five energy bands, using the same frequency and the first/second frequency derivatives as mea-

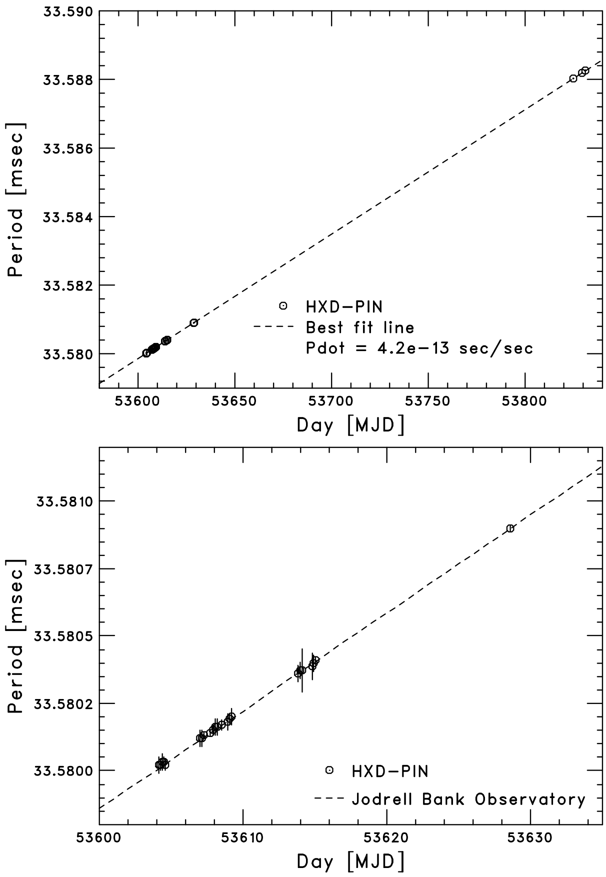

Figure 2. (Top) Barycenter-corrected and temperature-compensated pulse periods of the Crab pulsar, obtained with HXD-PIN in 2005 August-September and in 2006 March-April. The dushed line is a linear fit to the Suzaku measurements, with a slope of $\dot{P} = 4.2 \times 10^{-13}$ s s^{-1}. (Bottom) The 2005 portion of the same period history as the top panel, but compared with the radio measurements at the Jodrell Bank Radio Telescope [7].

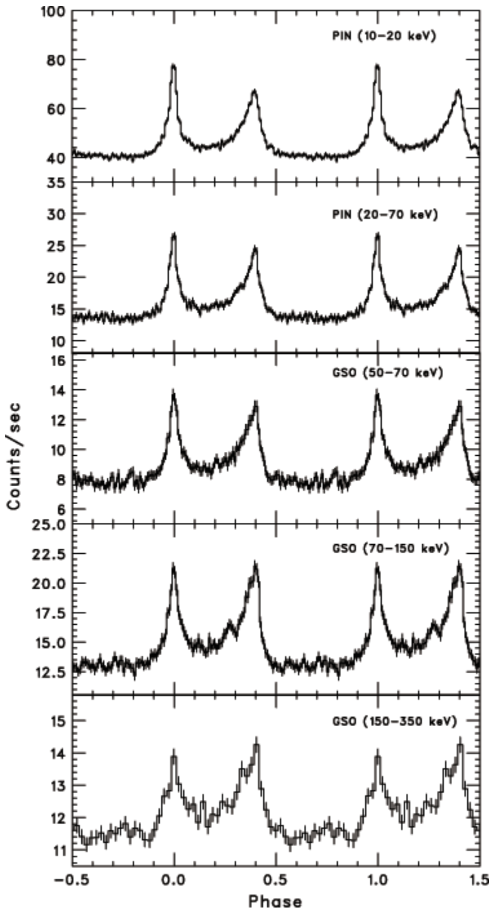

Figure 3. Folded light curves of the Crab pulsar, obtained on 2005 September 15 in 5 energy bands (10-20 keV and 20-70 keV for HXD-PIN, while 50-70 keV, 70-150 keV and 150-350 keV for HXD-GSO). The nebular emission and backgrounds are included. Phase 0.0 is defined to coincide with the peak of the radio main pulse.

sured with the Jodrell Bank Radio Telescope, and assingning the phase orgin (0.005) to the radio main-pulse peak. Since the main peak in the HXD pulse profile is obtained at a phae of 0.00 ± 0.01, we confirmed that the HXD has an absolute timing accuracy better than 600 μs. In addition, the observed pulse profiles agree with those measured in past observations.

The temperatur-dependent clock drift (of the order of 10^{-8} s s^{-1}; § 1) is 3 order of magnitude smaller than the Doppler effect due to the spacecraft revolution around the Earth, and is hence generally negligible in determining the instantaneous Crab pulse period. However, it can accumulate to a few msec, over a typical time scale of a few days on which the spacecraft temperature changes. Therefore, the temperature compensation of the DP clock becomes important in examining the absoluete Crab pulse phase as presented in Fig3. The successful alignment between the radio and hard X-ray pulse phases (Fig3) indicates that the DP clock attains a secular stability of $\sim 10^{-9}$ s s^{-1} after corrected for the temperature changes.

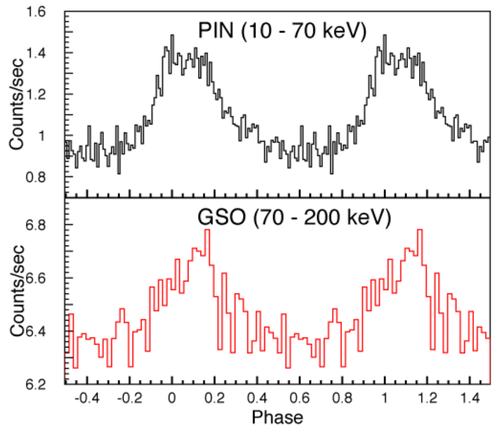

Figure 4. Two-band light curves of PSR 1509-58 folded at the 151.35 msec pulse period. 10-70 keV data taken with HXD-PIN and those in 70-200 keV taken with HXD-GSO are shown.

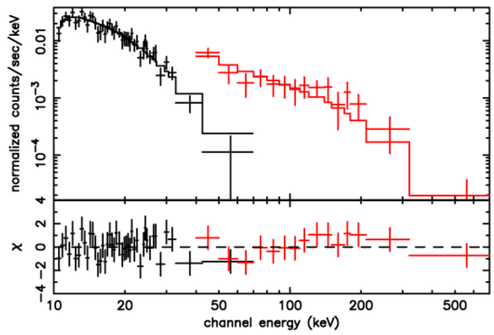

Figure 5. The HXD-PIN and HXD-GSO spectra of PSR 1509-58, obtained on 2005 August 23. Instrumental responses are not removed. The solid histgrams show a single power-law with a photon index 1.7.

3. *SUZAKU* RESULTS ON X-RAY PULSARS

3.1. The young neutron star PSR 1509-58

The rotation-powered pulsar PSR 1509-58 was observed on 2005 August 23 for 45 ksec exposure, mainlly aiming at timing calibration. We successfuly detected the pulsation at a barycentric period of 151.35 mse, by the power spectra and folding analysis. The light curves folded at this period are shown in Fig.4. Figure 5 shows the pulsed-component spectra, which were derived by subtracting off-pulse (phae 0.9-0.4) data from on-phase (phase 0.4-0.9) ones. The spectra extends to neary 200 keV (3σ detectionn) with a photon index of 1.7 ± 0.2, in agreement with previous measurements (e.g., $\Gamma = 1.64^{+0.43}_{-0.42}$ [8] and $\Gamma = 1.48 \pm 0.06$ [9]). This demonstrates the high sensitivity and good timing accuracy of the HXD.

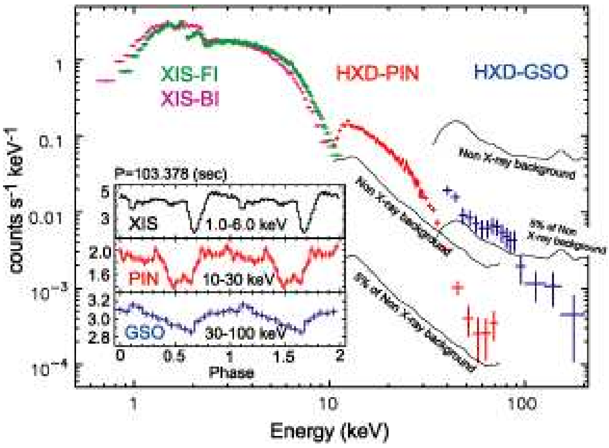

Figure 6. Background-subtracted wide band spectra of A0535+26. The inset shows folded light curves obtained with the XIS, HXD-PIN, and HXD-GSO [10].

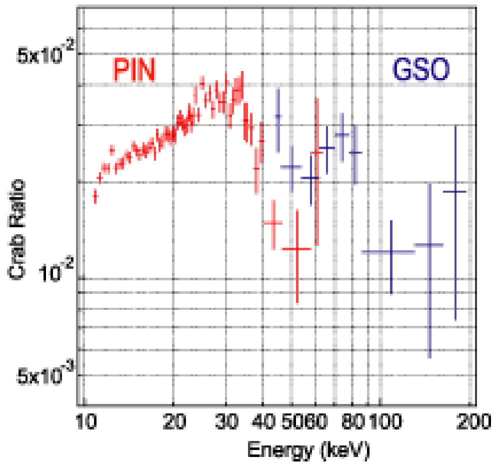

Figure 7. Background-subtracted spectra of A0535+26, nomalized to that of the Crab Nebula. The cyclotron resonance appears around 46 keV [10].

3.2. The binary X-ray pulsar A0535+26

The recurrent Be-transient pulsar A0535+26 was observed on 2005 September 14 for an exposure of 22 ksec, at a declining phase of a minor outburst [10]. The wide-band spectra of the XIS, HXD-PIN, and HXD-GSO are shown in Fig.6. In spite of the very low source intensity (about 30 mCrab at 20 keV), its electron cyclotron resonance was detected with the HXD, in absorption at about 46 keV (Fig.7). The HXD-GSO spectrum is suggestive of the 2nd harmonic absorption at ~ 110 keV, although its significance is not high enough if we consider systematic errors of the background subtractions [10]. Even at this low luminosity, $\sim 3.7 \times 10^{35}$ erg/s (at an assumed distance of 2 kpc), the resonance energy remains the same as previous values measured when the source was two order of magnitude more luminous. This makes an intersting contrast to another Be-transiant pulsar 4U 0115+63, of which the resonance energy is luminosity dependent [11]. We also utilized the resonance feature to reconfirm the energy-scale alignment between PIN and GSO.

4. CONCLUSION

After bacycentric and temperature corrections, the pulsations of the Crab pulsar were successfully detected at correct periods as predicted by radio observations. The absolute timing of the Crab pulse peak agreed between the HXD and radio observations within 600 μs, Thus, we have confirmed that the timing capability of the HXD and *Suzaku* in functioning as designed.

The pulsed component spectra of PSR 1509-58 extend to nearly 200 keV, with a photon index of 1.7 ± 0.2. This demonstrates the high sensitivity and the good timing accuracy of the HXD.

The cyclotron absorption feature of A0535+26 was successfully detected with the HXD, when the resonance was nearly two orders of magnitude fainter than in previous outbursts in which the source were detected. The resonance energy remains the same as that measured at more luminous state.

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