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A GIANT GLITCH IN THE ENERGETIC 69 MILLISECOND X-RAY PULSAR AXS J161730−505505

KEN'ICHI TORII,[1] E. V. GOTTHELF,[2] G. VASISHT,[3] T. DOTANI,[4] AND K. KINUGASA[5]
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ABSTRACT

We present new results on the recently discovered 69 ms X-ray pulsar AXS J161730−505505, the sixth youngest example of a rotation-powered pulsar. We have undertaken a comprehensive X-ray–observing campaign of AXS J161730−505505 with the *ASCA*, *BeppoSAX*, and *RXTE* observatories and follow its long-term spin-down history between 1989 and 1999 using these observations and archival *Ginga* and *ASCA* data sets. The spin-down is not simply described by a linear function as originally thought, but instead we find evidence of a giant glitch ($|\Delta P/P| \gtrsim 10^{-6}$) between 1993 August and 1997 September, perhaps the largest yet observed from a young pulsar. The glitch is well described by steps in P and $\dot{P}$ accompanied by a persistent $\ddot{P}$ similar to those seen in the Vela pulsar. The pulse profile of AXS J161730−505505 presents a single asymmetric peak that is maintained over all observation epochs. The energy spectrum is also steady over time, characterized by a highly absorbed power law with a photon index $\Gamma = 1.4 \pm 0.2$, consistent with that found for other young rotation powered pulsars.

Subject headings: pulsars: general — pulsars: individual (AXS J161730−505505, PSR J1617−5055) — stars: neutron — supernova remnants — X-rays: general

1. INTRODUCTION

Radio pulsars are thought to be highly magnetized ($\sim 10^{12}$ G), rapidly spinning neutron stars whose luminosity is powered by rotational energy loss. The study of young ($<10^5$ yr) rotation-powered pulsars provides an important laboratory for understanding the early evolution (thermal, spin, and magnetic) of these embers of stellar collapse. The most energetic of these pulsars are observable at X-ray wavelengths, which allow us to probe these extreme, but rare, examples.

In addition to uniform spin-down corresponding to the rotational energy loss, rotation-powered pulsars show sudden discontinuities in their rotation periods (see Lyne & Graham-Smith 1998). These rare phenomena, known as "glitches," are considered to arise from sudden changes in the configuration of superdense material in the neutron star interior. To date, a total of 71 glitches with $|\Delta P/P| > 10^{-9}$ have been reported in 30 pulsars (Urama & Okeke 1999). Observation of pulsar glitches gives us insights into the structure and physical processes inside the neutron stars, such as the interactions of neutron superfluid and crust components (e.g., Anderson & Itoh 1975).

In this Letter, we report the detection of a giant glitch from AXS J161730−505505 by using newly acquired and archival multimission X-ray data. This source is an unusual case of a young pulsar discovered first by its X-ray emission, revealed during the course of an archival X-ray study of the supernova remnant (SNR) RCW 103 (Gotthelf, Petre, & Hwang 1997). Further analysis detected highly significant pulsations from photons attributed to this source (Torii et al. 1998), consistent with a 69 ms pulse period reported from a *Ginga* observation of the region (Aoki, Dotani, & Mitsuda 1992). A recent radio observation has confirmed AXS J161730−505505 as a young energetic rotation-powered pulsar (Kaspi et al. 1998). The lack of evidence for this object in archival soft X-ray images suggests that the source might be highly absorbed, making it difficult to determine whether or not it is associated with an SNR.

2. OBSERVATIONS

A set of day-long X-ray observations of the field containing RCW 103, 1E 61348−5055, and AXS J161730−505505 was performed with the *ASCA* (Tanaka, Inoue, & Holt 1994), *BeppoSAX* (Boella et al. 1997), and *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993) observatories. In Table 1, we summarize the set of observations presented in this work.

Imaging data were acquired with the Gas-Imaging Spectrometers (GISs) on board *ASCA* and with the Medium-Energy Concentrator (MECS) instruments on *BeppoSAX*. These instruments have moderate imaging ($\sim 2'$) and spectral resolution ($\sim$8% at 6 keV) over an energy bandpass of 0.7–10 keV (GIS) and 1.5–12 keV (MECS), with a field of view (FOV) large enough to cover the SNR and pulsar simultaneously. Nonimaging data were obtained with the Proportional Counter Array (PCA) on board the *RXTE*, which provides a broader energy bandpass (2–60 keV) at lower spectral resolution ($\sim$16% at 6 keV). The PCA FOV is roughly circular with an $\sim 1^\circ$ FWHM response. The GIS data were collected in the highest time resolution mode (0.5 ms or 61 μs, depending on the data acquisition mode) whose measured absolute accuracy is 200 μs in this mode (Saito et al. 1997). The PCA data were collected using the good xenon mode with 0.9 μs timing resolution. For the current analysis, the absolute timing uncertainty is $\sim$100 μs (Rots et al. 1998). Photons collected by the MECS are time tagged with 15 μs resolution. We do not include data from *ASCA*'s Solid-state Imaging Spectrometers (SISs) since the pulsar fell just off the edge of its FOV, nor do we include data from *BeppoSAX*'s other instruments because the observing time is insufficient for these instruments to measure the pulsar periodicity reliably since a part of the observation was interrupted prematurely.

[1] Space Utilization Research Program, Tsukuba Space Center, National Space Develop Agency of Japan, 2-1-1, Sengen, Tsukuba, Ibaraki, 305-8505, Japan; torii.kenichi@nasda.go.jp.

[2] Columbia Astrophysics Laboratory, 550 West 120th Street, New York, NY 10027; evg@astro.columbia.edu.

[3] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; gv@astro.caltech.edu.

[4] Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan; dotani@astro.isas.ac.jp.

[5] Gunma Astronomical Observatory, 6860-86, Nakayama, Takayama, Agatsuma, Gunma, 377-0702, Japan; kinugasa@astron.pref.gunma.jp.

TABLE 1
TIMING DATA FOR AXS J161730−505505

Number	Satellite/Observatory	Instrument	Observation Date[a]	Exposure (s)	Epoch[b] (MJD)	Period[c] (ms)
1	*Ginga*	LAC[d]	1989 Mar 4	14,400	47,590.2	69.31890(3)
2	*ASCA*	GIS	1993 Aug 17	35,353	49,217.277625	69.338019(2)
3	*ASCA*	GIS	1997 Sep 4	58,063	50,696.736757	69.355301(1)
4	*RXTE*	PCA	1998 Jan 2	33,712	50,816.132391	69.356717(1)
5	Parkes	64 m	1998 Jan 15	...	50,829.7	69.356889(7)[e]
6	*BeppoSAX*	MECS	1998 Sep 17	16,288	51,073.892337	69.359778(1)
7	*ASCA*	GIS	1999 Feb 12	15,405	51,222.279184	69.361532(4)
8	*ASCA*	GIS	1999 Feb 20	16,232	51,229.708310	69.361624(7)
9	*RXTE*	PCA	1999 Mar 5	37,253	51,243.247065	69.3617824(5)
10	*ASCA*	GIS	1999 Mar 6	20,700	51,243.354377	69.361782(8)
11	*BeppoSAX*	MECS	1999 Mar 23	38,197	51,261.461543	69.362000(3)
12	*ASCA*	GIS	1999 Mar 26	18,914	51,263.519288	69.362021(3)
13	*BeppoSAX*	MECS	1999 Aug 4	53,115	51,394.834928	69.363568(2)
14	*ASCA*	GIS	1999 Sep 13	17,796	51,434.716949	69.364037(6)

[a] Start time of the observation.
[b] Middle time of the observation, except for the radio ephemeris.
[c] The 1 σ error of the last significant figure is shown in parentheses.
[d] Large Area Counter.
[e] The radio ephemeris reported here (V. Kaspi 1999, private communication) has been revised from that given in Kaspi et al. 1998.

Each data set was processed through its standard pipeline reduction for that mission and edited to exclude times of high background contamination using the standard screening criteria. This rejects time intervals of South Atlantic Anomaly passages, Earth occultations, the bright Earth limb in the FOV (*ASCA* and *BeppoSAX* only), and other periods of high-particle activity. The resulting effective observation times are summarized in Table 1. For each observation, event data from all detectors were co-added, and the arrival times of each event were corrected to the solar system barycenter using the software TIMECONV (*ASCA*), BARYCONV (*BeppoSAX*), or FXBARY (*RXTE*).

3. RESULTS

3.1. *Timing*

The X-ray images obtained with both *ASCA* and *BeppoSAX* above 3 keV reveal AXS J161730−505505 to be 4′ outside the SNR shell (see Fig. 1 of Gotthelf et al. 1997; see also Gotthelf, Petre, & Vasisht 1999). To increase the signal-to-noise ratio for detecting pulsations from the pulsar, we extracted photons from an 8′ diameter aperture centered on the pulsar, restricting the energy range of extracted photons to 3–10 keV for GIS and 3–12 keV for the other instruments. For the PCA data, in this energy band, we further restrict our search to layer 1 data only, which provides the best sensitivity for a Crab-like spectrum. For the higher energy analysis afforded by the PCA, above ∼12 keV, we used data from all three PCA layers.

We searched each data set for the expected 69 ms period predicted from the initial period and period-derivative measurement (Torii et al. 1998). A periodogram was constructed using the χ^2 statistic to test against a null hypothesis. For each trial period, we folded the data into 10 bins and computed the χ^2 of the resultant profile. We search a narrow range of periods centered on the expected period ± 0.1 ms, sampled in increments of $0.1P^2/T$, where T is the observation duration and P is the test period. A highly significant signal was detected from each of our data sets.

As well as the newly obtained data, we have reanalyzed the previous *Ginga* and *ASCA* data (Aoki et al. 1992; Torii et al. 1998) in a uniform way and revised the period and its error by using the method of Leahy (1987). Our X-ray–timing results derived from these 13 measurements are listed in Table 1 along with an updated radio ephemeris (V. Kaspi 1999, private communication).

3.2. *Spectrum*

We search for spectral dependence of the pulse profile by comparing the folded light curves in several energy bands. No strong energy dependence is evident in the energy-resolved light curves. Furthermore, the pulse amplitude and pulse profile remained unchanged between observational epochs.

We examined the *ASCA* and *BeppoSAX* data on AXS J161730−505505 for any long-term changes in its energy spectrum or flux. As for the timing analysis, we restrict our comparison to the energy range above 3 keV and extract photons from an 8′ diameter aperture centered on the source. We fitted the spectrum with a power-law function modified by interstellar absorption. The absorption was fixed at 6.8×10^{22} cm^{-2} (Torii et al. 1998). Spectra from each observation were found to be consistent with each other. Combining the seven *ASCA* observations, we obtain the pulse-phase–averaged photon index, $\Gamma = 1.4 \pm 0.2$, and the observed flux of $(3.6 \pm 0.2) \times 10^{-12}$ ergs s^{-1} cm^{-2} (90% confidence errors) in the 3–10 keV range, which is consistent with the previous measurement (Torii et al. 1998).

4. DISCUSSION

A χ^2 fit to all 14 data points, as summarized in Table 1, gives the mean spin-down rate of $\dot{P} = 1.3611(1) \times 10^{-13}$ s s^{-1} and $P = 0.069347150(1)$ at MJD 50,000.0 (Fig. 1). However, the quality of the fit is bad, with χ^2/degrees of freedom (dof) = 4808/12. The residual of the fit shows a jump of $\Delta P \simeq -1.2 \times 10^{-7}$ s between the observations of 1993 August (MJD 49,217.6) and 1997 September (MJD 50,696.0) (Fig. 2, *top panel*). Within the observation span of 10 yr, the residual is neither periodic nor smooth. A sudden change in the period between MJD 49,217.6 and MJD 50,696.0 is suggested. We consider that a glitch, similar to those observed in several young rotation-powered pulsars, is the most likely explanation for these residuals.

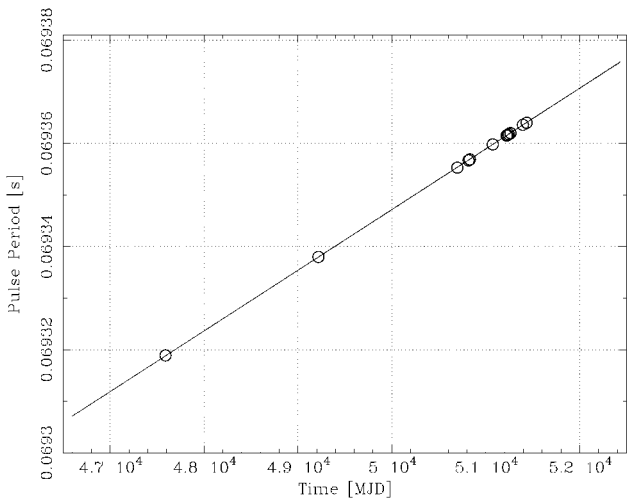

FIG. 1.—Pulse-period evolution of AXS J161730−505505 over 10 yr

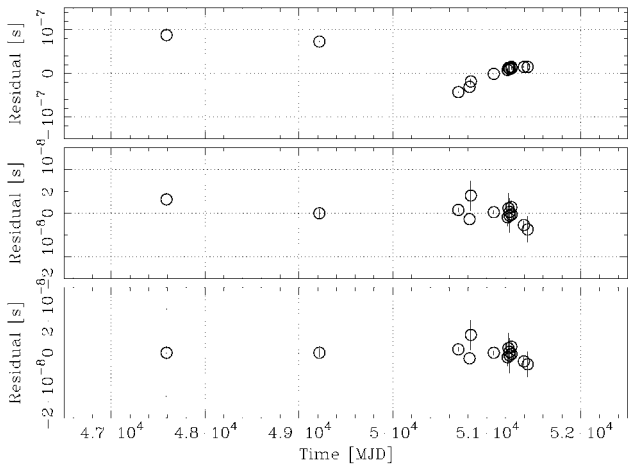

FIG. 2.—*Top*: Pulse-period residual as fitted by a linear function. *Middle*: Pulse-period residual as fitted to eq. (1) with a glitch at MJD 50,000. *Bottom*: Pulse-period residual as fitted to eq. (2) with a glitch at MJD 50,000.

Given the clear evidence of glitch activity, we next attempted to model the spin-down data with a single glitch followed by an exponential recovery. The data coverage is limited, and we simply assumed the following relation for the spin-down:

$$P(t) = P_0 + \dot{P}(t - t_0) + \Delta P \exp\left(-\frac{t - t_0}{\tau}\right), \qquad (1)$$

where $\Delta P = 0$ for $t < t_0$ and ΔP is a negative constant for $t \geq t_0$. This model contains five parameters, which, except for the depth of the glitch ΔP, are found to be independent of the time of the glitch, t_0. The derived parameters P_0, $\dot{P}$, ΔP, and τ are summarized in Table 2 for assumed values of t_0 = 49,300.0, 50,000.0, and 50,600.0 MJD. The residual for t_0 = 50,000 is shown in the middle panel of Figure 2. The quality of the fit is now characterized by χ^2/dof = 22.6/10.

The size of the glitch depends strongly on the unknown glitch epoch t_0. The fractional increase in rotation was found to be $\Delta P/P = -4.2 \times 10^{-6}$ for t_0 = 50,000.0 MJD (fixed), while it changes between $\Delta P/P = -11 \times 10^{-6}$ for t_0 = 49,300.0 MJD (fixed) and $\Delta P/P = -1.8 \times 10^{-6}$ for t_0 = 50,600.0 MJD (fixed). The minimum fractional increase in rotation rate is therefore comparable to those of the largest known pulsar glitches (Lyne et al. 1996a; Shemar & Lyne 1996).

Using the above model, the recovery time following the glitch episode is found to be τ = 700 days. This duration is somewhat unusual compared with the radio pulsars whose recovery time is seen to bifurcate between $\tau \simeq 100$ days and $\tau \geq 1000$ days (Shemar & Lyne 1996). Our derived value lies squarely between these two timescales, perhaps because of the simple model we invoked that allows for only a single glitch. Because of the sparse data coverage between 1993 August and 1997 September, however, we cannot determine whether the recovery time could be expressed as the sum of the two timescales.

Glitches found in radio pulsars may be classified into three groups (Lyne & Graham-Smith 1998). The first is a Crab-like glitch that is characterized by steps mainly in $\dot{P}$. The second is a Vela-like glitch that is characterized by large changes in P ($\Delta P/P \simeq -10^{-6}$) and the exponential recoveries. For the Vela pulsar, linear sawtooth changes in $\dot{P}$ have been observed between glitches (Lyne et al. 1996b). The third kind is often found in old pulsars and is characterized by a change in P.

Since the large glitch found for AXS J161730−505505 is similar in its magnitude to those in the Vela pulsar, a phenomenological model taking into account the sawtooth behavior may be a good description. Apart from short-term effects, the spin-down for the Vela pulsar is expressed by a linear change in spin-down rate. Therefore, the following function is appropriate if the transient effects have already ceased by MJD 50,696:

$$P(t) = P_0 + \Delta P_0 + (\dot{P} + \Delta\dot{P})(t - t_0) + \frac{1}{2}\ddot{P}(t - t_0)^2. \qquad (2)$$

Here $\Delta P_0 = 0$ and $\Delta\dot{P} = 0$ for $t < t_0$, and they are constant values ($\Delta P_0 < 0$ and $\Delta\dot{P} > 0$) for $t \geq t_0$. This model contains six parameters. Again, the time of the glitch, t_0, had to be assumed. The derived parameters are summarized in Table 3. For the condition that $\Delta P_0 < 0$, t_0 was restricted to $t_0 \lesssim 50{,}205$. The residual for t_0 = 50,000 is shown in the bottom panel of Fig-

TABLE 2
BEST-FIT PARAMETERS OF A GIANT GLITCH IN AXS J161730−505505 FOR EQUATION (1)

	VALUES OF t_0		
PARAMETER	MJD 49,300 (fixed)	MJD 50,000 (fixed)	MJD 50,600 (fixed)
P_0 (s)[a]	0.069338991(2)	0.069347220(3)	0.069354272(5)
$\dot{P}$ (s s^{-1})	$1.3605(5) \times 10^{-13}$	$1.3605(5) \times 10^{-13}$	$1.3605(5) \times 10^{-13}$
ΔP (s)	$-8(2) \times 10^{-7}$	$-2.9(2) \times 10^{-7}$	$-1.26(4) \times 10^{-7}$
τ (days)	$7(1) \times 10^2$	$7(1) \times 10^2$	$7(1) \times 10^2$

[a] The period just before the glitch at t_0.

TABLE 3
BEST-FIT PARAMETERS OF A GIANT GLITCH IN AXS J161730−505505 FOR EQUATION (2)

PARAMETER	VALUES OF t_0		
	MJD 49,300 (fixed)	MJD 50,000 (fixed)	MJD 50,205 (fixed)
P_0 (s)	0.069338980(3)	0.06934707(3)	0.06934943(3)
ΔP_0 (s)	$-4.6(3) \times 10^{-7}$	$-1.0(2) \times 10^{-8}$	$-3.1(3) \times 10^{-10}$
$\dot{P}$ (s s^{-1})	$1.344(3) \times 10^{-13}$	$1.332(5) \times 10^{-13}$	$1.328(5) \times 10^{-13}$
$\Delta\dot{P}$ (s s^{-1})	$5.8(7) \times 10^{-15}$	$5.8(7) \times 10^{-15}$	$5.8(7) \times 10^{-15}$
$\ddot{P}$ (s^{-1})	$-2.0(3) \times 10^{-23}$	$-2.0(3) \times 10^{-23}$	$-2.0(3) \times 10^{-23}$

ure 2. The quality of the fit is significantly improved to χ^2/dof = 17.1/9. Compared with the fit to equation (1), the *F*-test gives a chance probability of ~0.1. This result suggests that transient effects had indeed ceased by MJD 50,696. The reduced χ^2 is still larger than unity, suggesting the presence of timing noise and smaller glitches.

We can estimate the expectancy of large ($|\Delta P/P| > 10^{-7}$) glitches by using the semiempirical relation based on the superfluid vortex unpinning model (Alpar & Baykal 1994). Using this relation, the expected number of large glitches between the first *Ginga* observation and the last *ASCA* observation is 3.7. Therefore, there should have been about four glitches of $|\Delta P/P| > 10^{-7}$. Indeed, the residuals to the fit of equation (1) or equation (2) still hint at a small jump of $\Delta P = -5 \times 10^{-9}$ s between MJD 51,263.8 (1999 March) and MJD 51,394.2 (1999 August). This may be another glitch of $\Delta P/P = -7 \times 10^{-8}$, much smaller in magnitude than the one near MJD 50,000 but still relatively large compared with those seen for most radio pulsars (Shemar & Lyne 1996). We have thus found a giant glitch of $|\Delta P/P| \gtrsim 10^{-6}$ at $t_0 \simeq$ 50,000 MJD (49,218 $\leq t_0 \leq$ 50,696) and possibly a glitch of $|\Delta P/P| \simeq 7 \times 10^{-8}$ at $t_0 \simeq$ 51,300 MJD (51,264 $\leq t_0 \leq$ 51,394).

The detection of a giant glitch from AXS J161730−505505 gives a rare sample for studying the origin of pulsar glitches and the interior structure of neutron stars. In this context, the regular timing observation of this pulsar in the radio band is quite important for monitoring the onset of a glitch and following transient effects. Long-term timing observations for measuring the braking index are desired. Searches for the highly absorbed X-ray emission from the supernova remnant associated with this pulsar should be undertaken with the next generation of X-ray observatories.

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REFERENCES

Alpar, M. A., & Baykal, A. 1994, MNRAS, 269, 849
Anderson, P. W., & Itoh, N. 1975, Nature, 256, 25
Aoki, T., Dotani, T., & Mitsuda, K. 1992, IAU Circ. 5588
Boella, G., Butler, R. C., Perola, G. C., Piro, L., Scarsi, L., & Bleeker, J. A. M. 1997, A&AS, 122, 299
Bradt, H. V., Rothschild, R. E., & Swank, J. H. 1993, A&AS, 97, 355
Gotthelf, E. V., Petre, R., & Hwang, U. 1997, ApJ, 487, L175
Gotthelf, E. V., Petre, R., & Vasisht, G. 1999, ApJ, 514, L107
Kaspi, V. M., Crawford, F., Manchester, R. N., Lyne, A. G., Camilo, F., D'amico, N., & Gaensler, B. M. 1998, ApJ, 503, L161
Leahy, D. A. 1987, A&A, 180, 275
Lyne, A. G., & Graham-Smith, F. 1998, Pulsar Astronomy (2d ed.; Cambridge: Cambridge Univ. Press), chap. 6
Lyne, A. G., Kaspi, V. M., Bailes, M., Manchester, R. N., Taylor, H., & Arzoumanian, Z. 1996a, MNRAS, 281, L14
Lyne, A. G., Pritchard, R. S., Graham-Smith, F., & Camilo, F. 1996b, Nature, 381, 497
Rots, A. H., et al. 1998, ApJ, 501, 749
Saito, Y., et al. 1997, *ASCA* Newsl., 5
Shemar, S. L., & Lyne, A. G. 1996, MNRAS, 282, 677
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
Torii, K., et al. 1998, ApJ, 494, L207
Urama, J. O., & Okeke, P. N. 1999, MNRAS, 310, 313