A PULSE PROFILE CHANGE POSSIBLY ASSOCIATED WITH A GLITCH
IN THE ANOMALOUS X-RAY PULSAR 4U 0142+61

Mikio Morii
Department of Physics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8551, Japan
morii@oasis.ttksc.jaxa.jp

Nohuyuki Kawai
Department of Physics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8551, Japan

Noriaki Shibazaki
Department of Physics, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan

Received 2004 June 16; accepted 2004 December 2

ABSTRACT

We report a glitchlike pulse-frequency deviation from the simple spin-down law in an anomalous X-ray pulsar (AXP), 4U 0142+61, detected by ASCA observations. We also found a significant change in pulse profile after the putative glitch. The glitch parameters resemble those found in another AXP, 1RXS J170849.0–400910, and in the Vela and other radio pulsars. This suggests that radio pulsars and AXPs have the same internal structure and glitch mechanism. It must be noted, however, that the pulse-frequency anomaly can also be explained by a gradual change of the spin-down rate without invoking a glitch.

Subject headings: pulsars: individual (4U 0142+61) — stars: neutron — X-rays: stars

Online material: color figures

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) are a small group of X-ray–emitting pulsars (see Mereghetti et al. 2002 for a review). These objects are not likely to be accretion-powered pulsars with a binary companion, as either the fluxes of the optical counterparts or the Doppler modulation due to binary motion has yet to be found. They are also not rotation-powered, since the observed X-ray luminosities ($L_X \sim 10^{34}–10^{36}$ ergs s$^{-1}$) exceed the spin-down energy-loss rates of neutron stars ($\dot{E} = 4\pi^2 IP^3/3 \sim 10^{32.6}$ ergs s$^{-1}$).

Accretion-powered pulsars without a binary companion (i.e., with fossil accretion disks; see Chatterjee et al. 2000; Alpar 2001) and those with a small binary companion (Mereghetti & Stella 1995) have been raised as possibilities. However, the pulse timing that would originate in an accretion disk (large timing noises or persistent spin-up periods) is not found. The AXPs 1E 2259+586 (Kaspi et al. 2003) and 1RXS J170849.0–400910 (Kaspi et al. 2000; Kaspi & Gavriil 2003) have exhibited glitches similar to those of rotation-powered pulsars.

The timing behavior of AXPs is similar to that of a solitary neutron star with no accretion disk. AXPs are also characterized by soft X-ray spectra ($\Gamma \geq 2$), a lack of radio detections, slow rotation periods (5–12 s), and burst activity.

Thompson & Duncan (1996, 2001) proposed the novel hypothesis that soft gamma-ray repeaters and AXPs are solitary neutron stars with ultrastong magnetic fields ($10^{14}–10^{15}$ G), referred to as “magnetars.” X-ray photons are produced in this model by release of the strong magnetic field energy stored in the neutron star’s crust or in a twisted internal magnetic field. Recent discoveries of burst activity (Gavriil et al. 2002; Kaspi et al. 2003), optical pulsation (Kern & Martin 2002), and cyclotron spectral features (Gavriil et al. 2002; Ibrahim et al. 2002, 2003; Rea et al. 2003) support the magnetar model. Interestingly, a glitch and pulse profile change were observed simultaneously during an outburst of 1E 2259+586 (Kaspi et al. 2003).

The X-ray source 4U 0142+61 was discovered by Uhuru; its pulsation period of 8.7 s was discovered by EXOSAT (Israel et al. 1994). This object is a prototype of the AXP class (Hellier 1994; Mereghetti & Stella 1995; van Paradijs et al. 1995). The discovery of optical pulsations supports the magnetar scenario by suggesting that the optical emission comes from the magnetosphere of the neutron star, not from an accretion disk (Kern & Martin 2002).

The long-term stability of the intensity, spectrum, and pulse profile of 4U 0142+61 were reported based on a comparison between ASCA observations in 1994 and in 1998 (Paul et al. 2000). High stability over 4.4 years was reported following long-term monitoring observations with the Rossi X-Ray Timing Explorer (RXTE) from 1996 November to 2001 April (Gavriil & Kaspi 2002), and the pulse frequency and its derivative were precisely determined. However, this RXTE observation was not complete, with a 2.0 yr gap from 1998 March to 2000 March dividing its total 4.4 yr duration into two spans, the first of 1.3 yr and the second of 1.1 yr (see Table 2 of Gavriil & Kaspi 2002 and Fig. 1 below). Gavriil & Kaspi combined these spans and provided unified ephemerides, “A” and “B,” which are qualitatively similar (Table 2 of Gavriil & Kaspi 2002).

The ASCA observations in 1998 and 1999 were performed just during the gap between the RXTE observations. Those in 1999 in particular were carried out over a period of a month, and therefore, precise determination of the pulse frequency was possible. We have discovered in our study that the pulse frequency of 4U 0142+61 in the 1999 ASCA observations was significantly higher than those predicted by the unified ephemerides.
(A, B) and the first-span ephemeris, and it is also marginally higher than the prediction from the second-span ephemeris. These deviations exclude the unified ephemerides and suggest the presence of a glitch within the 2.0 yr gap before the 1999 ASCA observations. In addition, we detect a morphological change in the X-ray pulses, in which the pulse profile after the glitch differed significantly from those observed before the glitch.

2. OBSERVATIONS

Pulsar 4U 0142+61 was observed with ASCA eight times during the satellite’s mission life. The observations were undertaken in 1994, 1998, and 1999. The source was monitored over a period of about 1 month with six exposures during the last term. These observations are summarized in Table 1. All the observations were taken with the GIS and SIS detectors. Almost all the GIS observations were taken in the pulse-height mode, with 1024 pulse-height bins and timing bit set to zero, at high or medium bit rate, in which the time resolutions are 62.5 and 500 ms, respectively. We analyzed only the GIS-2 and GIS-3 data with high and medium bit rates.

We obtained all the ASCA observation data for 4U 0142+61 from the High Energy Astrophysics Science Archive Research Center. We used the SCREENED data, which had been subjected to the standard screening procedure (Revision 2). We selected the source photons from a circular region with a radius of 5.9 centered on the position with the pulsar peak counts, and we used events with an energy of 0.5 to 10 keV (values of 44–848 in pulse-invariant space). The source flux was constant and we used events with an energy of 0.5 to 10 keV (values of 5\(^{-10}\)).

### TABLE 1

| Reference Epoch (MJD) | \(\nu\) (Hz) | \(\dot{\nu}\) (Hz s\(^{-1}\)) | Start Date (UT) | Exposure (ks) |
|-----------------------|-------------|-----------------|-----------------|-------------|
| 49.614.17288----------- | 0.1151016(8) | ... | 1994 Sep 18 (21:35:39) | 18.4 |
| 51.046.69875----------- | 0.1150972(6) | ... | 1998 Aug 21 (11:23:48) | 18.9 |
| 51.403.13258----------- | 0.115097645(4) | \(-2.4^{+0.5}_{-0.7} \times 10^{-14}\) | 1999 Jul 29 (16:22:15) | 23.2 |
| 1999 Aug 3 (20:03:29) | 23.5 |
| 1999 Aug 9 (18:37:56) | 11.0 |
| 1999 Aug 12 (22:24:03) | 19.4 |
| 1999 Aug 21 (19:06:08) | 25.1 |
| 1999 Aug 27 (03:01:19) | 18.1 |

Note.—Reference epochs are given at mid-observation. Numbers in parentheses are 1σ uncertainties.

3. TIMING ANALYSIS

We proceeded with the following steps to determine the pulse frequencies (\(\nu\)) and their derivatives (\(\dot{\nu}\)) for the observation terms of 1994, 1998, and 1999, on the assumption that the higher order derivatives were zero. We calculated both values at a reference epoch (\(t_0\)), which was selected at the middle of the observation terms, to minimize the effect of the correlated error between \(\nu\) and \(\dot{\nu}\). Hereafter, a subscript zero denotes a parameter evaluated at the reference epoch \(t_0\).

3.1. Epoch-folding Method

Rough (\(\nu_0, \dot{\nu}_0\)) pairs were estimated by the epoch-folding method, in which the best (\(\nu_0, \dot{\nu}_0\)) pair was taken to be that which maximized the quantity \(S\) from each folded light curve:

\[
S = \sum_{j=1}^{n} \frac{|N_j - \langle N_j \rangle|^2}{\sigma_{N_j}^2} = \sum_{j=1}^{n} \frac{|N_j - \langle N_j \rangle|^2}{(1 - 2/n) N_j + N/n^2},
\]

where \(n = 16\) is the number of bins in one period, \(N_j\) (\(j = 1, 2, \ldots, n\)) is the number of events in the \(j\)th bin, \(N = \sum_{j=1}^{n} N_j\) is the total number of events in the observation term, and \(\langle N_j \rangle = N/n\) is the mean number of events for the bins.

3.2. Pulse Arrival Time Analysis

More accurate determinations of the pulse frequency and its uncertainty were achieved by counting the pulse numbers and the pulse arrival times. The pulse numbers uncertainty were achieved by counting the pulse numbers and imposing a constraint on the segment pulses in which the cumulative pulse phase \(\phi_{\text{cum}}(t_i)\) of the \(i\)th segment relative to the template must be an integer (\(N_i\)) plus the phase offsets (\(\Delta N_i\)).

---

2 At http://heasarc.gsfc.nasa.gov/docs/archive.html.
The best combination of the $N_i$ ($i = 1, 2, \ldots, n_{seg}$) and $(\nu_0, \dot{\nu}_0)$ pair was found by minimizing the following $\chi^2$ value:

$$
\chi^2(\nu_0, \dot{\nu}_0; N_1, N_2, \ldots, N_{n_{seg}}) = \sum_i \frac{[\phi_{bst}(t_i; \nu_0, \dot{\nu}_0) - (N_i + \Delta N_i)]^2}{\sigma_{\Delta N_i}^2}.
$$

(2)

Here $N_i$ was selected within the error of $\phi_{bst}(t_i)$ derived from the uncertainties in the $(\nu_0, \dot{\nu}_0)$ roughly determined by the epoch-folding method. The uncertainties for $(\nu_0, \dot{\nu}_0)$ can be calculated appropriately, because this analysis uses the $\chi^2$ fitting method.

4. RESULTS

4.1. Pulse-Frequency History

The pulse frequencies and their derivatives obtained from the ASCA observations are listed in Table 1. The observations in 1994 and 1998 were too short to determine $\nu$, and therefore we calculated only the $\nu$ by setting $\dot{\nu} = 0$ for these terms. The spin-down history is shown in Figure 1. The frequencies from the ASCA observations in 1994 and 1998 are consistent with all the RXTE ephemerides (Gavriil & Kaspi 2002). However, the frequency for 1999 is significantly higher than the unified ephemerides (A or B) and the first-span ephemeris, and marginally higher than the second-span ephemeris (Fig. 2). The frequencies at the reference epoch of the 1999 ASCA observations expected on the basis of the RXTE ephemerides (Gavriil & Kaspi 2002) are listed in Table 2. The same table also indicates the probability of the null hypothesis that the frequency from the ASCA observations and those predicted from RXTE are the same.
4.2. Pulse Profile

We next searched for pulse profile changes. We first compared the pulse profile of each segment among the 1999 observations with the template pulse profile. The pulse phases of the segment pulse profiles were aligned with the template using the same cross-correlation procedure used in the pulse arrival time analysis (\S 3.2). Each segment pulse profile \(D\) was fitted to the template pulse profile \(T\) to minimize the following reduced \(\chi^2\) statistic by adjusting parameters \(a\) and \(b\):

\[
\chi^2 = \frac{1}{n-2} \sum_{j=1}^{n} \frac{(D_j - (aT_j - b))^2}{\sigma^{2}_{D_j}}.
\]

Here \(n = 16\) is the number of phase bins and \(D_j\) and \(T_j\) are respectively the number of events in the \(j\)th bin of the segment and the template pulse profiles. The number of degrees of freedom is \(\nu = n - 2\).

There were no significant variations (\(\chi^2 \leq 1.4\) for 14 degrees of freedom, corresponding to a probability of 0.14) of the pulse profiles during the observations in 1999 (Fig. 3). However, the template pulse profiles in 1994 and in 1998 differed significantly from that in 1999, with \(\chi^2\) of 3.8 and 5.9. The residuals from the adjusted 1999 template pulse profile are also shown. [See the electronic edition of the Journal for a color version of this figure.]

5. DISCUSSION

This is the first discovery of a significant frequency deviation from the simple spin-down law in 4U 0142+61. It is unlikely that this deviation was caused by timing noise, because the timing solutions were good during the RXTE observations (first and second spans) and the 1999 ASCA observations. The most likely interpretation of this frequency jump is a glitch. The increase in the frequency \((\Delta \nu / \nu)\) can be constrained, assuming that the glitch happened between MJD 50,893.00 (the end of the first RXTE observation span) and MJD 51,389.18 (the first of the 1999 ASCA observations) (Fig. 1, bottom). The increase in the spin-down rate can be estimated to be \(\Delta \nu / \nu = (1.4 \pm 0.5) \times 10^{-2}\) if the \(v\)-difference in the RXTE first- and second-span ephemerides (Table 2 of Gavriil & Kaspi 2002) was caused by this glitch. Interestingly, this value is similar to that for a glitch in another AXP, 1RXS J170849.0–400910 (“glitch 1” in Kaspi & Gavriil 2003). These values are also similar to those seen in the Vela radio pulsar and other young radio pulsars (see Kaspi et al. 2000 and references therein).

We have also detected a significant pulse profile change in 4U 0142+61 for the first time, which may be associated with the glitch. This phenomenon is reminiscent of an outburst that occurred in another AXP, 1E 2259+586, with regard to the following points (Kaspi et al. 2003): (1) the amplitudes of the two peaks in the pulse profile were swapped during the outburst in 1E 2259+586; and (2) 1E 2259+586 also underwent a sudden spin-up of magnitude \(\Delta \nu / \nu = 4 \times 10^{-6}\). This could be interpreted to suggest that 4U 0142+61 underwent an occasional outburst, as well as a pulse profile change and a glitch, just before the 1999 ASCA observations. Nonetheless, it must be noted that the lack of a pulse profile change during the 1999 ASCA observations suggests that the survival time of the changed pulse profile is more than 1 month, longer than the considerably shorter-lived (~6 days) pulse profile change observed in 1E 2259+586.

The \(\Delta \nu / \nu\) and \(\Delta \nu / \nu\) values observed in AXPs glitches are similar to those of rotation-powered pulsars, and therefore the inner structure of the neutron stars and the glitch mechanisms may be basically the same. Both types of neutron star may consist of a neutron superfluid inner part and an outer crust, and the glitches occur as the result of angular momentum transfer from the inner superfluid to the crust caused by a catastrophic vortex motion. However, the pulse periods of AXPs (~10 s) are beyond the cutoff of the glitch occurrence, at which periods the stress of the Magnus force is not strong enough to trigger a glitch (see Fig. 8 of Ruderman et al. 1998). This suggests that there is a difference in the mechanism that causes these pulsars to reach the critical state of a glitch; for example,
the ordinary rotation-powered pulsars may reach the critical state because of their spin-down, while the magnetar candidates do so because of the stress of their magnetic fields.

The pulse profile change suggests two possibilities: (1) Large-scale reconnection of the magnetic field or deformation of the magnetosphere, or (2) a plasma ejection from the crust into the magnetosphere (maybe a burst) that changes the distribution of the plasma emitting the X-ray photons. The association between the pulse profile change and the glitch suggests the following scenarios: (a) The glitch is associated with crust cracking (Ruderman et al. 1998; Link & Epstein 1996) or platelet movement (Ruderman 1991), which causes deformation of the crust, and the pulse profile then changes as a result of possibility 1; or (b) plasma ejection from the crust is associated with catastrophic vortex motion (a glitch) and the pulse profile changes because of the occurrence of possibility 1 or possibility 2.

We note that the observed ephemeris inconsistency can be explained without assuming a glitch. It is possible that the spin-down rate was temporarily lower for a period between the 1998 RXTE observation and the 1999 ASCA observations, as observed in the AXP 1E 1048.1–5937 (Gavriil & Kaspi 2004). If the period of the smaller spin-down rate begins at the end of the 1998 RXTE observation and ends with the start of the 1999 ASCA observations, the spin-down rate in that period becomes minimal: it is $\dot{\nu} = -2.49(3) \times 10^{-14}$ Hz s$^{-1}$, corresponding to a 5.9% ± 1.2% change from the spin-down rate of the 1998 RXTE observation. This lower limit on the $\dot{\nu}$ change is consistent with the finding for 1E 1048.1–5937 (Gavriil & Kaspi 2004). Such behavior could be caused by a change in the magnetospheric structure, followed by a torque change and possibly by the pulse profile change.

6. CONCLUSION

An analysis of ASCA observations suggests the occurrence of a glitch in 4U 0142+61. The glitch is similar to those observed in another AXP, 1RXS J170849.0–400910, and other young radio pulsars. This indicates that the radio pulsars and AXPs have the same internal structures and glitch mechanisms. However, the source of the stress triggering the glitch may be different. We also discovered a pulse profile change, which may be associated with this glitch. This suggests that AXPs possess an association between the internal structure and the magnetosphere that does not exist in radio pulsars.

This work was partially supported under the 21st Century Center of Excellence program “Nanometer-Scale Quantum Physics” at the Tokyo Institute of Technology by the Ministry of Education, Culture, Sports, Science, and Technology, Japan. This research was also supported in part by a Grant-in-Aid for Scientific Research (C), No. 15540239. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA’s Goddard Space Flight Center.

REFERENCES

Alpar, M. A. 2001, ApJ, 554, 1245
Chatterjee, P., Hernquist, L., & Narayan, R. 2000, ApJ, 534, 373
Gavriil, F. P., & Kaspi, V. M. 2002, ApJ, 567, 1067
———. 2004, ApJ, 609, L67
Gavriil, F. P., Kaspi, V. M., & Woods, P. M. 2002, Nature, 419, 142
Hellier, C. 1994, MNRAS, 271, L21
Ibrahim, A. I., Safi-Harb, S., Swank, J. H., Parke, W., Zane, S., & Turolla, R. 2002, ApJ, 574, L51
Ibrahim, A. I., Swank, J. H., & Parke, W. 2003, ApJ, 584, L17
Israel, G. L., Mereghetti, S., & Stella, L. 1994, ApJ, 433, L25
Kaspi, V. M., & Gavriil, F. P. 2003, ApJ, 596, L71
Kaspi, V. M., Gavriil, F. P., Woods, P. M., Jensen, J. B., Roberts, M. S. E., & Chakrabarty, D. 2003, ApJ, 588, L93
Kaspi, V. M., Lackey, J. R., & Chakrabarty, D. 2000, ApJ, 537, L31
Kern, B., & Martin, C. 2002, Nature, 417, 527
Link, B., & Epstein, R. I. 1996, ApJ, 457, 844
Mereghetti, S., Chiarlone, L., Israel, G. L., & Stella, L. 2002, in Neutron Stars, Pulsars and Supernova Remnants, ed. W. Becker, H. Lesch, & J. Trümper (MPE Rep. 278) (Garching: MPI extrater. Phys.), 29
Mereghetti, S., & Stella, L. 1995, ApJ, 442, L17
Paul, B., Kawasaki, M., Dotani, T., & Nagase, F. 2000, ApJ, 537, 319
Rea, N., Israel, G. L., Stella, L., Oosterbroek, T., Mereghetti, S., Angelini, L., Campana, S., & Covino, S. 2003, ApJ, 586, L65
Ruderman, M. 1991, ApJ, 382, 587
Ruderman, M., Zhu, T., & Chen, K. 1998, ApJ, 492, 267 (erratum 492, 267 [1998])
Thompson, C., & Duncan, R. C. 1996, ApJ, 473, 322
———. 2001, ApJ, 561, 980
van Paradijs, J., Taam, R. E., & van den Heuvel, E. P. J. 1995, A&A, 299, L41
White, N. E., Angelini, L., Ebisawa, K., Tanaka, Y., & Ghosh, P. 1996, ApJ, 463, L83