X-Ray Timing of the Young Pulsar in 3C 58

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Abstract. PSR J0205+6449 is a young pulsar in the Crab-like pulsar wind nebula 3C 58 which is thought to be a result of the historical supernova SN1181 CE. The 65.7-ms pulsar is the second most energetic of the known Galactic pulsars and has been shown to be remarkably cool for its age, implying non-standard cooling processes in the neutron star core. We report on RXTE timing observations taken during AO7 and supplemented by monthly radio observations of the pulsar made with the Green Bank Telescope (GBT). The total duration covered with the timing solutions is 450 days. We measure very high levels of timing noise from the source and find evidence for a “giant” glitch of magnitude $\Delta \nu/\nu \sim 1 \times 10^{-6}$ that occurred in 2002 October. We have also measured the phase-resolved spectra of the pulsations and find them to be surprisingly hard, with photon indices $\Gamma = 0.84^{+0.06}_{-0.15}$ for the main pulse and $\Gamma = 1.0^{+0.4}_{-0.3}$ for the interpulse assuming an absorbed power-law model.

1. INTRODUCTION

PSR J0205+6449 was discovered in the heart of 3C 58 in Chandra HRC data and immediately confirmed in archival RXTE data by Murray et al. [1]. Camilo et al. [2] soon thereafter found extremely faint radio pulsations from the pulsar using the new Green Bank Telescope (GBT). Chandra ACIS-S observations taken by Slane, Helfand, & Murray [3] showed that the temperature of the neutron star (NS) is significantly below that predicted by standard NS cooling models given the very young age of the pulsar ($\sim 822$ yrs). Measurement of the spin period ($65.686 \text{ ms}$) and spin-down rate ($\dot{P} = 1.94 \times 10^{-13} \text{s/s}$) of the pulsar have allowed the estimation of several key parameters using the canonical expressions from pulsar theory:

- Spin-down energy
  \[ \dot{E} = 4\pi^2 I \dot{P}/P^3 = 2.7 \times 10^{37} \text{erg/s} \]  

- Surface magnetic field strength
  \[ B = \sqrt{3c^3I \dot{P}}/8\pi^2R^6 = 3.6 \times 10^{12} \text{Gauss} \]

- Characteristic age
  \[ \tau = P/(2\dot{P}) = 5400 \text{yr} \]

Each of these parameters is typical for young pulsars. One unusual point is that if the pulsar really is 822 yrs old and has been spinning down with the canonical braking index (due to magnetic dipole braking) of $n = 3$, then it must have been born spinning relatively slowly with $P_0 \sim 60 \text{ ms}$. Interestingly, the 65-ms PSR J1811−1925 in G11.2−0.5 seems to be an identical twin in many respects (see Roberts et al., these proceedings).

2. OBSERVATIONS AND DATA PREPARATION

We analyzed all available RXTE PCA data on 3C 58, which totaled more than $\sim 410 \text{ ks}$ of on-source time. The data came from OBSIDs P20259 ($\sim 20 \text{ ks}$), P60130 ($\sim 100 \text{ ks}$), and P70089 ($\sim 300 \text{ ks}$), and were taken in GoodXenon mode which provided events with time resolutions of $\sim 122 \mu s$ and 256 energy channels in the energy range $\sim 2-60 \text{ keV}$. Most observations were taken using 3 PCUs.

We processed the RXTE data using standard FTOOLS\(^1\) in order to filter out non-Level 1 events or those recorded outside of Good Time Intervals and to convert their arrival times to the Solar System barycenter (using the DE200 planetary ephemeris [4]). We determined the X-ray pulse times-of-arrival (TOAs) with a maximum-

\(^1\) http://heasarc.gsfc.nasa.gov/docs/software/ftools/ftools_menu.html
likelihood technique that we developed which assumed a two-Gaussian model of the X-ray pulse profile. A signal-
to-noise ratio optimization procedure allowed us to determine that the best energy range to use for the timing
analysis is $\sim 2-16$ keV (energy channels 4–39 inclusive), and so we filtered out events outside of this en-
ergy range (see the profile in Figure 1). A single time-of-
arrival (TOA) typically comprised one or two RXTE or-
bits depending on the background levels and the number of PCUs on. Since the observations consisted of between 4–6 orbits, we measured 3–4 TOAs each month with precisions of 100–200 $\mu$s each.

The GBT data were taken with the Berkeley-Caltech Pulsar Machine (BCPM)\(^2\) backend at either 820 MHz or 1400 MHz. The BCPM is an analog/digital filterbank which samples each of $2 \times 96$ channels using 4-bits at flexible sampling rates and channel bandwidths [5]. The data were recorded using 134 MHz of bandwidth and 50 $\mu$s samples for the 1400 MHz observations or 50 MHz of bandwidth and 72 $\mu$s samples for the 820 MHz observ-
ations. Typical integrations lasted between 4–8 hrs. We de-dispersed and folded all of the data using the pulsar analysis package PRESTO [6]. Each observation yielded 2–3 TOAs which we measured by correlating (in the fre-
quency domain) the folded pulse profile with a Gaussian of fractional width 0.04 in phase. The typical precision
of the radio TOAs was 200–400 $\mu$s.

FIGURE 1. RXTE Pulse Profile. The 2–16 keV pulse pro-
file for PSR J0205+6449 for RXTE OBSIDs P20259, P60130,
and P70089. The total integration time included over 400 ks with 3 PCUs and over 100 ks with either 4 or 5 PCUs. The solid grey bands show the portions of the pulse used for the phase-
resolved spectroscopy described in §4 with the pulse on the left and the interpulse on the right. The lightly hashed regions were used to compute the spectral background.

3. TIMING

The timing behavior and therefore the spin-down rate of PSR J0205+6449 is extremely noisy. Determining a phase-connected timing solution would have been im-
possible using the RXTE or GBT data alone. Thankfully, the cadence of the monthly observations in the radio
and X-ray bands was sufficiently different such that the ob-
servations complemented each other and usually allowed unambiguous pulse numbering between observations.

We applied time corrections to transform all the TOAs to UTC at the Solar System Barycenter using faxbary and TEMPO\(^3\) for the RXTE and GBT data respectively.

This absolute timing shows that the X-ray main pulse is delayed relative to the radio pulse (Camilo et al., in prep).

We performed all timing model fits with TEMPO.

Our data show that a “giant” glitch ($\Delta \nu/\nu \sim 1 \times 10^{-6}$) occurred near MJD 52555 (see Figure 2). The timing
solution prior to the glitch consists of a 6 parameter fit (spin frequency $\nu$ plus 5 frequency derivatives) resulting
in RMS timing residuals of $\sim 0.6$ ms. The post-glitch
timing solution consists of the spin frequency plus 2 frequency derivatives resulting in RMS timing residuals of $\sim 1.2$ ms. Additional frequency derivatives in the post-
glitch solution improve the residuals but are not required
for phase connection\(^4\). The residuals from the GBT and
RXTE for both timing solutions are shown in Figure 3.

FIGURE 2. A “Giant” Glitch. The thick lines correspond to the phase-coherent timing models described in §3. The thin grey lines correspond to the average spin-down as measured during the $\sim 210$ days before and after MJD 52555. The fractional difference in spin frequency between the two timing so-
lutions is $\Delta \nu/\nu \sim 1 \times 10^{-6}$, which is comparable in magnitude to the glitches from the older and also “cool” Vela pulsar.

\(^2\) http://www.gb.nrao.edu/~dbacker

\(^3\) http://pulsar.princeton.edu/tempo

\(^4\) While we believe that the post-glitch data is phase-connected, the sparse sampling and high levels of timing noise make it possible that we have miscounted pulses between one or more of the observations.
FIGURE 3. Post-fit Timing Residuals. Timing residuals for pre-glitch (left) and post-glitch (right) timing solutions. TOA precision is about $3 \times$ better with RXTE (the “X”s) than with the GBT at 820 MHz (the circles) at 1400 MHz (the squares) per unit of telescope time. The obvious systematic trends are the result of very large levels of timing noise from the pulsar. We lost phase connection near MJD 52555 due to the glitch shown in Figure 2. In both the pre- and post-glitch solutions, the measured braking index is much greater than the canonical value of 3, which is typical of timing noise or glitch recovery.

4. PHASE-RESOLVED SPECTROSCOPY

Figure 4 shows the results of absorbed power-law fits to the phase-resolved spectra of the pulsar’s main pulse and interpulse as determined using the FTOOL fasebin. We analyzed events from each PCU independently for each OBSID, combined these for each AO, and then combined the three AOs together. We fit the spectra with xspec after subtracting the average off-pulse background as shown in the hatched region in Figure 1 and freezing the value of $N_H = 3.62 \times 10^{21}$ cm$^{-2}$ based on the recent Chandra ACIS observation of 3C 58 (Slane et al., in prep). Fits made to the summed PCU data and simultaneously to the 5 PCUs independently were consistent within the statistical errors to one another.

The measured photon indices $\Gamma = 0.84^{+0.06}_{-0.08}$ for the main pulse and $\Gamma = 1.0^{+0.4}_{-0.3}$ for the interpulse are surprisingly hard. These values are difficult to reconcile with the $\Gamma = 1.73 \pm 0.07$ photon index measured with Chandra for the central point source [3], although significant nebular emission within the selection region could explain some of the spectral softening. Recent results from the 350 ks Chandra observation of 3C 58 place an approximate upper limit of $1.5 \times 10^{14}$ erg cm$^{-2}$ s$^{-1}$ for any hard component in the range 0.5—10 keV. But our fits to the main pulse alone predict fluxes in the same energy band at least one hundred times larger. We note that our measurements are consistent within the errors with the phase-resolved spectral fits of Gotthelf [7] ($\Gamma = 1.11 \pm 0.34$ for the pulsed emission) based on the RXTE data from P60130.

5. FUTURE PROSPECTS

With its young age, low temperature, very noisy spin-down, high $\dot{E}$, hard pulsed spectrum, and large glitches, the pulsar at the center of 3C 58 is certainly an object worth watching in the future. Is the extremely high level of timing noise from the pulsar somehow related to its “cool” temperature? Are both of these strange properties related to a more fundamental characteristic of the neutron star such as its mass? We are optimistic that continued monitoring of this unusual source will tell us something about the interior structure and internal dynamics of neutron stars. In addition, we note that the narrow pulse profile and hard spectrum of the pulsed emission from J0205+6449 make it an ideal and possibly unique target for INTEGRAL and other upcoming hard X-ray missions.

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FIGURE 4. Phase-Resolved Spectroscopy. The spectra of the main X-ray pulse (top) and interpulse (bottom) as fit from 3–16 keV with an absorbed power-law model. The $N_H$ was fixed at $3.62 \times 10^{21} \text{cm}^{-2}$ based on the recent 350 ks Chandra ACIS observation of 3C 58 (Slane et al., in prep). The best fit photon indices are surprisingly hard: $\Gamma = 0.84^{+0.06}_{-0.15}$ for the main pulse and $\Gamma = 1.0^{+0.4}_{-0.3}$ for the interpulse.