Crab Pulsar Glitch Monitoring with the National Time Service Center 40-meter Radio Telescope: Postprint

Authors: Dai Shun, Sun Pengfei, Liu Haiwen, Li Yifeng, Zhao Chengshi, Luo Jintao

Date: 2021-03-30T00:00:00+00:00

Abstract

Pulsar period glitch is a rare phenomenon that serves as a probe for studying the internal structure of pulsars. Using data from the Crab pulsar monitored by the 40-meter radio telescope at the Haoping Observatory of the National Time Service Center during pulsar timing observations from February to December 2019, we employed the pulsar timing method and analyzed it with the TEMPO2 fitting program. The results demonstrate that the Crab pulsar underwent a glitch phenomenon around July 23, 2019 (MJD58687), with a spin frequency increment of Δvg = 5.33(4)\$×\$10-7 Hz, a fractional spin change of Δvg /v = 17.9 (1) \$×\$10-9, and an accompanying exponential recovery process with a recovery factor Q ~ 0.88. The monitoring and processing of this Crab pulsar period glitch validates the pulsar monitoring capability of the 40-meter radio telescope at the National Time Service Center, while simultaneously accumulating a sample for investigating the generation mechanism of glitches.

Full Text

Monitoring of Crab Pulsar Glitches with the 40-meter Radio Telescope of the National Time Service Center*

Dai Shun[1],[2], **Sun Pengfei**[2], **Liu Haiwen**[3], **Li Yifeng**[2], **Zhao Chengshi**[2], **Luo Jintao**[2],[4]

[1]East China Jiaotong University, Nanchang 330013, China
[2]National Time Service Center, Chinese Academy of Sciences, Xi' an 710600, China
[3]Xi' an Jiaotong University, Xi' an 710049, China
[4]Key Laboratory of Precision Navigation and Timing Technology, National Time Service Center, Chinese Academy of Sciences, Xi' an 710600, China

Abstract

Pulsar glitches are rare phenomena that serve as probes for studying the internal structure of neutron stars. Using time-of-arrival measurements collected for the Crab pulsar from February to December 2019 with the 40-meter radio telescope at Haoping Observatory of the National Time Service Center, we analyzed the data using pulsar timing methods and the TEMPO2 fitting program. Our results reveal that the Crab pulsar experienced a glitch around July 23, 2019 (MJD 58687), characterized by a rotational frequency increment of Δ _g $= 5.33(4) \times 10^{-7}$ Hz, corresponding to a fractional change of Δ _g/ $= 17.9(1) \times 10^{-9}$, followed by an exponential recovery process with a recovery coefficient Q ~ 0.88. This detection and analysis of the Crab pulsar glitch demonstrate the monitoring capabilities of the 40-meter radio telescope at the National Time Service Center and contribute valuable samples for investigating the mechanisms underlying glitch phenomena.

Keywords: glitches; pulsar; Crab pulsar; timing residuals

Pulsars are rapidly rotating neutron stars with extremely strong magnetic fields, whose long-term stability can rival that of atomic clocks [1]. Some pulsars exhibit two types of rotational instabilities: timing noise and glitches. Timing noise is a widespread, continuous, small-amplitude fluctuation phenomenon in pulsars [2], more pronounced in those with large period derivatives and generally displaying quasi-periodic characteristics. Glitches, by contrast, manifest as sudden increases in rotation rate, typically followed by recovery processes lasting from weeks to years [3]. These events are relatively rare and occur sporadically, making them unpredictable [4]. Among the 2,872 known pulsars, 567 glitches have been detected in 190 pulsars.

Most observed glitch events show no significant changes in radiation characteristics, suggesting that glitches are likely associated with changes in the internal structure of pulsars rather than magnetospheric phenomena. Two primary theoretical models currently explain glitch mechanisms: the starquake model [5] and the vortex model [6]. The starquake model posits that glitches result from crustal deformation in pulsars—specifically, the steady rotational slowdown disrupts the equilibrium between gravitational and centrifugal forces, causing sudden contraction and rotational acceleration. The vortex model suggests that during pulsar spin-down, the internal superfluid and outer crust rotate at different angular velocities. When the crust rotates slower than the core and the coupling force does not exceed a certain threshold, vortices pinned in the crustal lattice can only move outward, transferring angular momentum to the crust [7] and causing the observed spin-up. The starquake model may apply to small-amplitude glitches, while the vortex model may be more suitable for large-amplitude events.

The Crab pulsar (PSR B0534+21 or PSR J0534+2200), discovered in 1968, formed from the supernova of 1054 AD and represents one of the youngest known pulsars [8]. With a rotation period of approximately 33 ms, a period derivative of about 4.2×10^{-13}, a magnetic field strength of ~4×10^{12} G, and multi-wavelength emission characteristics [9], the Crab pulsar’ s relatively unstable internal structure makes it an ideal probe for studying neutron star interiors through glitch events.

This paper presents observations from the 40-meter telescope at Haoping Observatory of the National Time Service Center, documenting a rotational glitch in the Crab pulsar around July 23, 2019. The following sections describe the observational data, data processing procedures, analysis of timing results, and concluding remarks.

1. Observations

The observations were conducted using the 40-meter Haoping Radio Telescope (HRT) of the National Time Service Center (NTSC), Chinese Academy of Sciences. Constructed in 2014 and located at Haoping Observatory in Luonan County, approximately 100 km east of Xi’an, the telescope is situated in the Qinling Mountains with excellent electromagnetic environmental shielding. HRT is a fully steerable Cassegrain single-dish antenna with a complete panel reflector [10]. The pulsar timing observation system is equipped with an L-band room-temperature receiver and an FPGA + GPU architecture digital backend. The receiver bandwidth is 800 MHz, operating in single circular polarization mode before November 2019 and upgraded to dual circular polarization thereafter. Coherent dedispersion mode was added starting in July 2019. The system noise temperature is approximately 100 K.

The Crab pulsar was observed at Haoping Observatory every 2–5 days with observation durations ranging from 10 to 75 minutes. The data used for this glitch study span from February 21 to December 8, 2019 (MJD 58534–58825), incorporating both incoherent and coherent dedispersion [11] observations. In incoherent dedispersion mode, the time resolution is 10.24 s with 1,024 frequency channels and 1,024 phase bins; in coherent dedispersion mode, the time resolution is 1.28 s with 1,024 frequency channels and 1,024 phase bins, and a sub-integration time of 10 s.

2. Data Processing Workflow

Timing observation data processing employs the PSRCHIVE preprocessing software and TEMPO2 timing analysis software. PSRCHIVE [12] is an open-source software package for scientific data analysis in pulsar astronomy, enabling calibration, statistical analysis, simulation, and visualization of pulsar timing data. TEMPO2 [13] is a timing software developed for pulsar timing array projects, using the International Celestial Reference System (ICRS) and complying with IAU 2000 resolutions, capable of fitting glitch parameters with nanosecond-level timing precision.

The data processing workflow is illustrated in Figure 1 [Figure 1: see original paper]. For HRT folded-mode data, we first use PSRCHIVE to remove radio frequency interference. The dedispersed sub-integrations are then summed in time, frequency, and polarization to obtain average pulse profiles. To determine accurate pulse arrival times, all observed pulse profiles are typically integrated to create a high signal-to-noise-ratio standard template, which is cross-correlated with each average profile to obtain site arrival times. To eliminate Earth motion effects, the solar system barycenter is treated as an inertial reference frame, and all arrival times are converted to barycentric arrival times using TEMPO2. The software fits observed arrival times against predicted times from the pulsar timing model to produce timing residuals. The solar system ephemeris DE405 and Barycentric Coordinate Time (TDB) are used for conversions. The pulsar phase and exponential recovery processes are given by Equations (1) and (2):

$$\phi(t) = \phi_0 + \nu t + \dot{\nu} t^2 + \ddot{\nu} t^3 \quad (1)$$

$$\nu(t) = \nu_0(t) + \Delta\nu_p + \Delta\dot{\nu}_p t + \Delta\ddot{\nu}_p t^2 + \Delta\nu_d e^{-t/\tau_d} \quad (2)$$

In Equation (1), ϕ_0 is the phase at $t = 0$, and ν, $\dot{\nu}$, $\ddot{\nu}$ are the pulsar' s rotation frequency and its first and second derivatives, respectively. In Equation (2), $\Delta\nu_p$, $\Delta\dot{\nu}_p$, and $\Delta\ddot{\nu}_p$ represent the permanent changes in rotation frequency and its derivatives after the glitch; $\Delta\nu_d$ is the recovery amplitude; and τ_d is the recovery timescale.

3.1 Preprocessing Results

A sample Crab pulsar profile from HRT observations processed with PSRCHIVE is shown in Figure 2 [Figure 2: see original paper], with a signal-to-noise ratio of approximately 33.445 and an integration time of about 95 minutes. The profile clearly displays three main components: the main pulse and interpulse near phases 0.3 and 0.7, respectively, and the precursor approximately 0.1 phase units before the main pulse. Table 1 presents the pre-glitch rotational parameters derived from PSRCHIVE processing.

3.2 Timing Observations and Analysis

TEMPO2 fitting of the Crab pulsar' s rotational frequency ν, its first derivative $\dot{\nu}$, and second derivative $\ddot{\nu}$ reveals a glitch event around July 23, 2019 (MJD 58687). The timing residuals are shown in Figure 3 [Figure 3: see original paper]. The evolution of rotational frequency and its derivative over time, obtained from arrival time fitting, is displayed in Figure 4 [Figure 4: see original paper], where the upper panel shows the post-glitch frequency deviation from its mean value, and the lower panel shows the time evolution of the frequency derivative. Table 2 lists the post-glitch parameters.

The glitch magnitude is Δ _g/ = 17.9(1) × 10^{-9}, representing one of the larger events for this pulsar. The frequency increment is Δ _g = 5.33(4) × 10^{-7} Hz, with a relative change in the frequency derivative of Δ˙_g/˙ = 3.43(4) × 10^{-4} and an absolute change of Δ˙ = -1.26(1) × 10^{-13} s^{-2}. Analysis of the post-glitch behavior indicates an exponential recovery process with amplitude Δ _d = 4.69256078(3) × 10^{-7}, recovery coefficient Q = Δ _d/Δ _g ~ 0.88, and recovery timescale τ_d = 8.3(3) days.

Comparing our results with the pulsar glitch statistics catalog shows that this event is recorded as Δ _g/ = 36.0(1) × 10^{-9}. Both values are of the same order of magnitude, with the numerical difference likely attributable to missing post-glitch data in the HRT observations.

4. Conclusion

Long-term timing observations of the Crab pulsar with the 40-meter radio telescope at Haoping Observatory of the National Time Service Center have detected a glitch around July 23, 2019. Processing and fitting of the observational data reveal a glitch magnitude of Δ _g/ = 17.9(1) × 10^{-9}, accompanied by an exponential recovery process with τ_d = 8.3(3) days and recovery coefficient Q ~ 0.88. While the physical mechanism of pulsar glitches remains not fully understood, pulsar timing observations continue to provide crucial insights into the internal structure of neutron stars.

References

[1] Taylor J H. Millisecond Pulsars: Nature's Most Stable Clocks [J]. Proceedings of the IEEE, 2002, 79(7): 1054-1062.

[2] GAO Xudong, ZHANG Shuangnan, FU Jianning. Research progress of timing noise of normal pulsar[J]. Progress in Astronomy, 2016, 34(2): 163-180.

[3] WANG Na, WU Xinji. Glitch of the radio pulsars[J]. Progress in Astronomy, 2000, 18(3): 229-237.

[4] ZHOU Shiji, ZHANG Jie, YUAN Jianping, et al. On pulsar glitches in PSR J1016-5857[J]. Journal of China West Normal University (Natural Sciences), 2018, 39(1): 78-81.

[5] Ruderman M, Zhu T, Chen K. Neutron star magnetic field evolution, crust movement and glitches [J]. Astrophysical Journal, 1997, 492(1): 267-280.

[6] Ruderman M A. Crust-breaking by neutron superfluids and the VELA pulsar glitches [J]. The Astrophysical Journal, 1975, 203(1): 213-222.

[7] LI Linsen. The impact of magnetic decay braking torque on the secular retardation of spin of two-components of pulsars[J]. Astronomical Research & Technology, 2020, 17(01): 21-26.

[8] Wang N, Wu X J, Manchester R N, et al. A Large Glitch in the Crab Pulsar [J]. Research in Astronomy and Astrophysics, 2001, 1(3): 195-199.

[9] ZHU Hongxu, TONG Minglei, YANG Tinggao, et al. Measured data processing and analysis for XPNAV-1[J]. Journal of Astronautics, 2019, 40(12): 1492-1500.

[10] Luo J T, Gao Y P, Yang T G, et al. Pulsar Timing Observations with Haoping Radio Telescope [J]. Research in Astronomy and Astrophysics, 2020.

[11] HUANG Yuxiang, WANG Min, HAO Longfei, et al. Comparative study between the coherent de-dispersion and the incoherent de-dispersion of pulsar signal[J]. Astronomical Research & Technology, 2019, 16(01): 16-24.

[12] Straten W V, Manchester R N, Johnston S, et al. PSRCHIVE and PSRFITS: Definition of the Stokes Parameters and Instrumental Basis Conventions[J]. Publications of the Astronomical Society of Australia, 2009, 27(1): 104-109.

[13] Hobbs G, Edwards R, Manchester R. TEMPO2: A New Pulsar Timing Package [J]. Monthly Notices of the Royal Astronomical Society, 2006, 6(S2): 189-192.

Funded by the National Natural Science Foundation of China (11973046, 91736207, 42030105, 11873050, U1831201).

Received: 2021-01-31; Author biography: Dai Shun, female, Master' s degree. Research direction: Radio interference detection and elimination. Email: 18888108586@163.com

Note: Figure translations are in progress. See original paper for figures.