

## A Possible $\gamma$ -Ray Pulsation from PSR J1740–5340B in the Globular Cluster NGC 6397 postprint

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### Abstract

Recently, a new radio millisecond pulsar (MSP) J1740–5340B, hosted in the globular cluster (GC) NGC 6397, was reported with a 5.78 ms spin period in an eclipsing binary system with a 1.97 days orbital period. Based on a modified radio ephemeris updated by tool tempo2, we analyze the 15 yr  $\gamma$ -ray data obtained from the Large Area Telescope on board the Fermi Gamma-ray Space Telescope and detect PSR J1740–5340B's  $\gamma$ -ray pulsation at a confidence level of  $4\sigma$  with a weighted H-test value of 26. By performing a phase-resolved analysis, the  $\gamma$ -ray luminosity in on-pulse interval of PSR J1740–5340B is  $L_\gamma = 3.8 \times 10^{33} \text{ erg s}^{-1}$  using NGC 6397's distance of 2.48 kpc. And  $\gamma$ -rays from the on-pulse part of PSR J1740–5340B contribute 90% of the total observed  $\gamma$ -ray emissions from NGC 6397. No significant  $\gamma$ -ray pulsation of another MSP J1740–5340A in the GC is detected. Considering that the previous four cases of MSPs in GCs, more data in  $\gamma$ -ray, X-ray, and radio are encouraged to finally confirm the  $\gamma$ -ray emissions from MSP J1740–5340B, especially starving for a precise ephemeris.

### Full Text

#### Preamble

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#### A Possible $\gamma$ -Ray Pulsation from PSR J1740–5340B in the Globular Cluster NGC 6397

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## Abstract

Recently, a new radio millisecond pulsar (MSP) J1740–5340B was discovered in the globular cluster (GC) NGC 6397, with a 5.78 ms spin period in an eclipsing binary system with a 1.97-day orbital period. Using a modified radio ephemeris updated with the tempo2 tool, we analyzed approximately 15 years of  $\gamma$ -ray data obtained from the Large Area Telescope on board the Fermi Gamma-ray Space Telescope and detected  $\gamma$ -ray pulsations from PSR J1740–5340B at a confidence level of  $4\sigma$  with a weighted H-test value of 26. Through phase-resolved analysis, the  $\gamma$ -ray luminosity of PSR J1740–5340B in the on-pulse interval is  $L_\gamma = 3.8 \times 10^{33} \text{ erg s}^{-1}$ , assuming NGC 6397's distance of 2.48 kpc. The  $\gamma$ -rays from the on-pulse portion of PSR J1740–5340B contribute 90% of the total observed  $\gamma$ -ray emissions from NGC 6397. No significant  $\gamma$ -ray pulsations were detected from another MSP, J1740–5340A, in the GC.

Considering the previous four cases of MSPs in GCs, additional data in  $\gamma$ -ray, X-ray, and radio bands are encouraged to finally confirm the  $\gamma$ -ray emissions from MSP J1740–5340B, particularly requiring a precise ephemeris.

**Key words:** gamma-rays: galaxies -(stars:) pulsars: individual (PSR J1740-5340B) -(Galaxy:) globular clusters: individual (NGC 6397)

## 1. Introduction

Globular clusters (GCs) are ancient celestial systems with typical ages exceeding  $10^{10}$  years, bound together by mutual stellar gravity and orbiting the Milky Way as satellites (e.g., Harris 1996). The extremely high stellar density ( $10^3\text{--}10^6 \text{ stars pc}^{-3}$ ) in GC cores provides favorable conditions for stellar interactions that form low-mass X-ray binaries (LMXBs). The formation rates in GCs are more than two orders of magnitude higher than elsewhere in the Galaxy (Clark 1975; Katz 1975). Millisecond pulsars (MSPs) are thought to be “recycled” pulsars that have been spun up to short periods of several milliseconds through accretion of mass and angular momentum from a companion star in mass-transfer binaries. Therefore, LMXBs are generally believed to be the progenitors of MSPs.

It is widely accepted that GCs are among the most prolific environments for MSP formation (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). Since the first MSP was detected in a GC (M28, also known as NGC 6626) by the Lovell 76 m radio telescope (Lyne et al. 1987), approximately 272 pulsars have been observed in 38 GCs within 20 kpc of the Galactic center, with over 90% being MSPs and 50% located in binary systems. Typically, radio MSPs are associated with  $\gamma$ -ray sources.

Thanks to the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope (Fermi-LAT; Atwood et al. 2009),  $\gamma$ -ray emissions from GCs were first detected in 47 Tucanae (Abdo et al. 2009). To date, approximately 40 GCs have been detected in  $\gamma$ -rays, as listed in the fourth Fermi-LAT source catalog for Data Release 3 (4FGL-DR3; Abdollahi et al. 2022) and reported in Abdo et al. (2010a), Kong et al. (2010), Tam et al. (2011), Eger & Domainko (2012), Zhou et al. (2015), Tam et al. (2016), Zhang et al. (2016), Lloyd et al. (2018), MAGIC Collaboration et al. (2019), Ndiyavala et al. (2019), Abdollahi et al. (2020), Ballet et al. (2020), Song et al. (2021), Yuan et al. (2022a, 2022b), Wu et al. (2022). The first  $\gamma$ -ray pulsation from an individual pulsar in a GC, PSR J1823–3021A, was reported in NGC 6624 (Freire et al. 2011) with a 5.44 ms spin period and a relatively high spin-down luminosity. Subsequently, Wu et al. (2013) and Johnson et al. (2013) independently reported the discovery of  $\gamma$ -ray pulsations from MSP B1821–24 in NGC 6626 (M28), with a spin period of 3.05 ms and a spin-down luminosity of  $2.2 \times 10^{36}$  erg s<sup>-1</sup>. Then in NGC 6652, Zhang et al. (2022b) reported the detection of  $\gamma$ -ray pulsations from PSR J1835–3259B, with a spin period of 1.83 ms and a spin-down luminosity of  $4.3 \times 10^{35}$  erg s<sup>-1</sup> (Gautam et al. 2022). Recently, Zhang et al. (2023) reported the fourth  $\gamma$ -ray pulsation from PSR J1717+4308A in NGC 6341 using the radio rotational ephemeris reported in Pan et al. (2020). These reports suggest that  $\gamma$ -ray emissions from GCs primarily arise from individual MSPs hosted within them.

NGC 6397 is located at a distance of 2.48 kpc (Baumgardt & Vasiliev 2021) in the southern constellation of Ara, making it one of the two nearest GCs. Its age has been estimated at 12.6 billion years (Correnti et al. 2018). The first MSP in this GC, J1740–5340A (at R.A. = 17 40 44 .589 and decl. =  $-53^{\circ}40'40.90$ ) with a 3.65 ms spin period, was reported by D’ Amico et al. (2001), Ferraro et al. (2001), Grindlay et al. (2001), and Bogdanov et al. (2010) in an eclipsing binary system with a 1.35-day orbital period.

Recently, Zhang et al. (2022a) reported the discovery of another radio MSP, PSR J1740–5340B, with a 5.78 ms spin period in an eclipsing binary system with a 1.97-day orbital period (at R.A. = 17 40 42 .626 and decl. =  $-53^{\circ}40'27.91$ ), using the Parkes radio telescope (also known as Murriyang) with an observing frequency band of 704–4032 MHz in Australia and the MeerKAT radio telescope with a frequency band of 856–1712 MHz in South Africa. The second MSP’s spin-down period derivative ( $\dot{P}$ ) is  $-5.93 \times 10^{-21}$  s s<sup>-1</sup>. Here, we updated the MSP’s radio ephemeris provided in Zhang et al. (2022a) using 15 years of Fermi-LAT data by employing the tempo2 tool.

We then carried out a detailed data analysis for the events around NGC 6397 collected by Fermi-LAT and detected a  $\gamma$ -ray pulsation from MSP J1740–5340B at a post-trial significance of  $4\sigma$ , which corresponds to a weighted H-test value of 26. Through phase-resolved analysis, the  $\gamma$ -ray emissions from the on-pulse interval contribute 90% of the total observed  $\gamma$ -rays from NGC 6397. Compared to the previous four cases, this is the only  $\gamma$ -ray MSP in a GC with a spin-up

period. The paper is organized as follows. We describe the Fermi-LAT data analysis and report the main results in Section 2, followed by timing analysis in Section 3. Summaries and discussions of our  $\gamma$ -ray results are presented in Section 4.

## 2. Fermi-LAT Data Analysis and Results

NGC 6397's  $\gamma$ -ray emissions were first detected by Zhang et al. (2016). In the fourth Fermi-LAT catalog Data Release 3 (4FGL-DR3), a  $\gamma$ -ray source named 4FGL J1741.1–5341 associated with NGC 6397 was cataloged in Abdollahi et al. (2020), Ballet et al. (2020), and Abdollahi et al. (2022), and it was also presented in the Fermi-LAT eight-year source catalog as FL8Y J1741.2-5342.

### 2.1. Data Preparation and Source Model

The LAT is a pair-conversion telescope on board the Fermi satellite sensitive to  $\gamma$ -rays with energies from 20 MeV to  $>500$  GeV. In our data analysis, we selected LAT events between 2008 August 4 and 2023 May 15 (MJD 54,683 to MJD 60,079) with energies between 0.1 and 500.0 GeV centered on 4FGL J1741.1–5341 at coordinates R.A. = 17 41 09 .790 and decl. =  $-53^{\circ}41'02.419$  (Abdollahi et al. 2022). Around the target, the latest Pass 8 (with evclass = 128 and evtype = 3) SOURCE class events within a  $20^{\circ} \times 20^{\circ}$  region of interest (RoI) were selected for the entire analysis. Events with zenith angles  $>90^{\circ}$  were removed to minimize contamination from background  $\gamma$ -rays from Earth's limb. We used a filter expression of “(DATA\_{QUAL}>0) && (LAT\_{CONFIG}==1)” to obtain high-quality data in good time intervals. The instrumental response function “P8R3\_{SOURCE}\_{V3}” and FermiTools version 2.2.0 were used in our analysis. To obtain the best-fit parameters for NGC 6397, a model file was created based on the 4FGL-DR3 catalog using the script make4FGLxml.py, which includes  $\gamma$ -ray sources within a  $25^{\circ}$  radius as well as two diffuse emission background components: Galactic and extragalactic isotropic diffuse emissions. We freed the flux normalizations and spectral shape parameters for sources within  $5^{\circ}$  of 4FGL J1741.1–5341, the normalizations for sources within  $5^{\circ}$ – $10^{\circ}$ , and the normalizations of the two diffuse backgrounds, while other  $\gamma$ -ray source parameters were fixed at their 4FGL-DR3 values.

A binned maximum likelihood analysis was then performed between the full dataset and the model file to derive the best-fit parameters. A best-fit model file was built for all  $\gamma$ -ray sources. In 4FGL-DR3, 4FGL J1741.1–5341 has a log-parabola (LP) spectral shape with formula  $dN/dE = (E/E_b)^{-a} \cdot \log(E/E_b)$ . An average photon flux of  $(3.7 \pm 0.8) \times 10^{-9}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  was obtained in the 0.1–500.0 GeV energy range. The best-fit spectral parameters are listed in Table 1, and their values are in good agreement with those reported in 4FGL-DR3.

Considering that  $\gamma$ -rays from GCs likely arise from MSPs hosted within them, a power-law with exponential cutoff (PLEC) spectral model,  $dN/dE = E^{\Gamma} \exp(-$

$E/E_c$ ), was used to model the  $\gamma$ -rays from NGC 6397. The PLEC model is typical for describing pulsars' spectral energy distributions (SED) in the 0.1–500.0 GeV range. For the PLEC model, the best-fit parameter values are listed in Table 1. The TS value for the PLEC model was 81.8, the average photon flux was  $(6.6 \pm 0.9) \times 10^{-9}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  in the 0.1–500.0 GeV range, and the integrated energy flux was  $(3.5 \pm 0.4) \times 10^{-12}$  erg  $\text{cm}^{-2} \text{s}^{-1}$ . Comparing the best-fit results of the LP and PLEC spectral models, the TS value from the PLEC model is slightly larger than that from the LP model.

The best-fit parameters with the PLEC model for the target were saved as the final model, and subsequent analysis was carried out based on them. Assuming a distance to NGC 6397 of  $2.48 \pm 0.02$  kpc (Baumgardt & Vasiliev 2021), its  $\gamma$ -ray luminosity is  $(2.5 \pm 0.3) \times 10^{33}$  erg  $\text{s}^{-1}$  under the assumption of isotropic emission.

**2.1.1. TS Maps Extraction** To reveal the  $\gamma$ -ray emissions from NGC 6397, a TS map covering a  $3^\circ \times 3^\circ$  region centered on 4FGL J1741.1–5341 in the 0.1–500.0 GeV range was created using the `gttsmap` tool, based on the best-fit model with 4FGL J1741.1–5341 removed, and is shown in the left panel of Figure 1. To exclude contamination from possible new nearby  $\gamma$ -ray sources not included in 4FGL-DR3, a residual TS map was created based on the same best-fit model, with the same spatial size as the TS map. The residual TS map is shown in the right panel of Figure 1. In this figure, the maximum TS value across all pixels is 13.4, far less than 25 (which corresponds to a detection significance of  $4\sigma$ ), indicating that no new  $\gamma$ -ray source appears around the target. From the residual map, we conclude that all  $\gamma$ -ray events around the target are well described by the  $\gamma$ -ray sources in the best-fit model file. After comparing the two maps, we find that a point source with a PLEC spectral model can describe the  $\gamma$ -ray emissions from NGC 6397 in the 0.1–500.0 GeV range very well. The two MSPs, J1740–5340A and J1740–5340B, are marked with a green plus sign and an orange cross, respectively, in Figure 1.

**2.1.2. Spectrum Extraction** We performed a spectral analysis based on the best-fit model. In this step, for the model file, we freed only the sources within  $10^\circ$  and the two background component normalizations, while fixing all other spectral shape parameters at their best-fit values. The 0.1–500.0 GeV energy range was divided into 12 equal logarithmically spaced energy bins, and the flux of NGC 6397 for each energy bin was obtained using binned likelihood analysis. The flux data points (i.e., the SED) were derived and are shown in Figure 2, where data points with TS values  $\geq 5$  were kept, while others are shown as 95% flux upper limits. From Figure 2, we can see that the  $\gamma$ -ray SED of NGC 6397 is well described by a PLEC model.

### 3. Timing Analysis

#### 3.1. $\gamma$ -Ray Pulse Profile

Due to the large point-spread function of Fermi-LAT, the two MSPs J1740–5340A and J1740–5340B in NGC 6397 cannot be resolved as independent  $\gamma$ -ray sources. In our analysis, if we fold the  $\gamma$ -rays from the GC based on the ephemeris of one pulsar, the  $\gamma$ -rays from the other will serve as background, evenly distributed in the phase-resolved light curve.

First, based on the ephemeris provided by Zhang et al. (2022a), we carried out a timing analysis of 0.1–500.0 GeV events around NGC 6397 within an aperture radius angle  $< \max(6.68 - 1.76 \log_{10}(E/\text{MeV}), 1.3)^\circ$ , as adopted in Abdo et al. (2010b). However, no significant pulse profile was detected over the 15-year Fermi-LAT observations.

We then used the  $\gamma$ -ray data to update the radio ephemeris by determining pulse times of arrival and cross-correlating the pulse profiles using the tempo2 tool (Hobbs et al. 2006). A similar process has been applied in Xing & Wang (2015) and Xing et al. (2022). In our analysis, the timing parameters (frequency derivatives from  $f_0$  to  $f_2$ ) were fixed at their known values provided in Zhang et al. (2022a), while only the higher-order frequency derivatives ( $f_3$ – $f_6$ ) were fitted (provided in supplementary material “ngc6397b.tar”). We then assigned pulse phases to the events using tempo2 with the Fermi plug-in (Ray et al. 2011). Their probabilities of originating from NGC 6397 were calculated with the Fermi tool gtsreprob and used as weights for the  $\gamma$ -ray events; the highest probability is 70.3%.

Considering the faint  $\gamma$ -ray flux of NGC 6397 compared to other  $\gamma$ -ray pulsars in 4FGL-DR3, the folded weighted  $\gamma$ -ray pulse profile was binned into ten phase intervals. The  $\gamma$ -ray pulse profile and a two-dimensional phaseogram are shown in panels (A) and (B) of Figure 3, respectively. In the folded pulse profile, count uncertainties for the phase bins were calculated following the method provided by Abdo et al. (2013). We also estimated the background count contribution from the two diffuse sources and neighboring  $\gamma$ -ray sources around 4FGL J1741.1–5341 in 4FGL-DR3. The value is 119.6, shown as a horizontal red dashed-dotted line in Figure 3, which is in good agreement with the lowest phase bin ( $119.4 \pm 2.3$ ) of the pulse profile at the fourth bin.

An H-test statistic was applied to the events using their pulse phases and corresponding probabilities, following the method provided by de Jager & Büsching (2010) and Kerr (2011). The curve of cumulative H-test values spanning the Fermi-LAT observations is shown in Figure 3(C). An H-test value of 25.8 was obtained, corresponding to a p-value of  $3.3 \times 10^{-5}$  ( $4.2\sigma$ ), given by  $p\text{-value} = e^{-(0.4 \times H)}$ . Our calculation is in agreement with those reported in Kerr (2011), Abdo et al. (2013), and Smith et al. (2019).

The radio pulse profile of PSR J1740–5340B is shown in panel (D) of Figure 3, drawn approximately from that reported in Zhang et al. (2022a).

We also carried out the same timing analysis for another MSP, PSR J1740–5340A, using the radio ephemeris reported by Ferraro et al. (2001), Grindlay et al. (2001), and Bogdanov et al. (2010). However, no significant  $\gamma$ -ray pulsation with a frequency consistent with this MSP was detected. Considering this trial factor, the trial number (N) is two. The false-alarm probability (FAP) was estimated by  $FAP = 1 - (1 - p)^N \approx 6.6 \times 10^{-5}$ , corresponding to  $4.0\sigma$ .

### 3.2. Phase-resolved Analysis

Based on the  $\gamma$ -ray pulse profile (Figure 3(A)), we defined the on-pulse phase interval ( $P_{\text{on}}$ ) as phases 0.7–1.3 and the off-pulse interval ( $P_{\text{off}}$ ) as phases 0.3–0.7, shown in Figure 3(A) with pink and blue shaded regions, respectively. We then performed likelihood analysis for events from the on- and off-pulse intervals to describe the corresponding  $\gamma$ -ray emissions from NGC 6397 using the PLEC model, and summarized the best-fit parameters in Table 1. For the on-pulse data, PSR J1740–5340B’s  $\gamma$ -ray luminosity is  $L_{\gamma} = (3.8 \pm 0.9) \times 10^{33} \text{ erg s}^{-1}$ . For the off-pulse interval, the  $\gamma$ -ray luminosity is  $L_{\gamma} = (0.4 \pm 0.3) \times 10^{33} \text{ erg s}^{-1}$ . Their TS values were 76.9 and 8.9, respectively. In the likelihood analysis of the off-pulse data, we fixed the spectral shape parameters at the values from the best-fit model because the target is not very significant in this phase interval. Based on the likelihood analysis results for the on- and off-pulse intervals, their TS maps (with the same region size as shown in Figure 1) were obtained by removing the target from the model files and are shown in Figure 4. Therefore, the  $\gamma$ -ray emissions from the on-pulse interval contribute 90% of the total observed  $\gamma$ -rays from NGC 6397.

## 4. Conclusion and Discussion

In 4FGL-DR3, approximately 40 GCs have been detected with  $\gamma$ -ray emissions, which are typically believed to originate from the collective contribution of numerous pulsars harbored within them. In NGC 6397, two MSPs—J1740–5340A and J1740–5340B—were detected in radio observations (D’Amico et al. 2001; Zhang et al. 2022a). Several scenarios have been proposed to explain the radiation mechanism of  $\gamma$ -rays from GCs. According to the pulsar magnetosphere model, pulsars are believed to emit  $\gamma$ -rays in the several GeV range through curvature radiation (Zhang & Cheng 2003). Additionally, as suggested in Du et al. (2012), GeV  $\gamma$ -rays can be produced through inverse Compton scattering processes involving surrounding soft photons and energetic electrons/positrons.

Motivated by the discovery of MSP J1740–5340B (Zhang et al. 2022a), we carried out data analysis for the  $\gamma$ -ray emissions from NGC 6397 using Fermi-LAT observations spanning from 2008 August 4 to 2023 May 15. Based on the updated radio ephemeris, we performed a timing analysis and detected  $\gamma$ -ray pulsations with a frequency consistent with the newly discovered MSP at a  $4\sigma$  confidence level. This positions it as the fifth  $\gamma$ -ray MSP discovered within a GC and, notably, the first one exhibiting a spin-up period. The TS maps and

SEDs of NGC 6397 were obtained based on the PLEC spectral model in the 0.1–500.0 GeV range and are shown in Figures 1 and 2, respectively.

From the residual TS map (right panel of Figure 1), we conclude that a point-like  $\gamma$ -ray source described by a PLEC model effectively characterizes the  $\gamma$ -ray emissions from NGC 6397. Through timing analysis, the background count contribution from the two diffuse sources and neighboring  $\gamma$ -ray sources in the model file was estimated and is shown in Figure 3(A) as a red dashed-dotted line. This value is in good agreement with the lowest count bin of the  $\gamma$ -ray pulse profile, implying that  $\gamma$ -rays from PSR J1740–5340B account for most of the observed  $\gamma$ -ray emissions (90%) from GC NGC 6397. The remaining 10% may come from the off-pulse emission of PSR J1740–5340B and/or the first pulsar J1740–5340A. This is also consistent with the off-pulse TS map in the phase-resolved analysis (right panel of Figure 4). Similar results have been reported for PSR J1835–3259B in NGC 6652 and PSR J1717+4308A in NGC 6341 by Zhang et al. (2022b, 2023), where the pulsed  $\gamma$ -ray component also contributes the majority of the total observed  $\gamma$ -rays from the GCs.

In the phase-resolved analysis, the TS values for the on- and off-pulse intervals are 76.9 and 8.9, respectively, strengthening our discovery of  $\gamma$ -ray pulsations from PSR J1740–5340B. The on-pulse luminosity is  $L_{\gamma} = 3.8 \times 10^{33} \text{ erg s}^{-1}$ , while the off-pulse luminosity is  $0.4 \times 10^{33} \text{ erg s}^{-1}$ . Assuming that MSPs in GCs share similar characteristics and emit comparable amounts of  $\gamma$ -rays, we can use the observed  $\gamma$ -ray luminosity to estimate the expected number of MSPs hosted within each GC. Using the off-pulse luminosity, we estimate the number of other MSPs ( $N_{\text{MSPs}}$ ) hosted within NGC 6397 to be 0.2 using the formula  $N_{\text{MSPs}} = L_{\gamma_{\text{off}}} / (\gamma \dot{E})$ , where  $\dot{E}$  is the average spin-down power of MSPs and  $\gamma$  is the average spin-down to  $\gamma$ -ray luminosity conversion efficiency. The value of  $\dot{E}$ ,  $3.0 \times 10^{34} \text{ erg s}^{-1}$ , was estimated by averaging Galactic field MSPs in the ATNF pulsar catalog, while  $\gamma = 0.08$  was derived from observations of the three nearest known MSPs as adopted in Abdo et al. (2009). We note that the intrinsic spin-down of MSPs is masked by the cluster's acceleration, making  $\dot{E}$  measurements inaccurate and  $\dot{E}$  estimation difficult for MSPs in GCs; hence our estimate is rather rough.

No significant difference was found between this  $\gamma$ -ray MSP J1740–5340B and previous ones detected in GCs (Freire et al. 2011; Johnson et al. 2013; Wu et al. 2013; Zhang et al. 2022b, 2023) in terms of  $\gamma$ -ray SEDs and numbers of known MSPs. In summary, those four MSPs are younger, with spin-down luminosities of  $(0.4\text{--}2.2) \times 10^{36} \text{ erg s}^{-1}$ , making them brighter than typical MSPs. PSR J1717+4308A has lower  $\gamma$ -ray luminosity, while PSR J1740–5340B hosted in the nearest GC NGC 6397 (at 2.48 kpc, one of the two nearest GCs) may have been detected by Fermi-LAT due to its proximity. We also show the schematic radio pulse profile from Zhang et al. (2022a) in Figure 3(D) to facilitate comparison with the  $\gamma$ -ray pulse profile, though not for alignment purposes. We recognize that aligning radio and  $\gamma$ -ray pulse profiles is technically challenging. Moreover, the ephemeris provided by Zhang et al. (2022a) lacks sufficient information for

establishing alignment, and the ephemeris used in this work was modified using Fermi-LAT data. Hence, we do not delve into topics concerning alignment between  $\gamma$ -ray and radio pulse profiles.

To confirm the  $\gamma$ -ray pulsation of PSR J1740–5340B, additional data from  $\gamma$ -ray, X-ray, and radio telescopes are encouraged, particularly requiring a precise ephemeris. Future  $\gamma$ -ray telescopes, such as the Very Large Area Gamma-ray Space Telescope (VLAST; Fan et al. 2022), may provide additional insights into this pulsar and related studies of  $\gamma$ -rays from GCs.

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**Data Availability:** The data underlying this work are available from the Fermi Science Support Center.

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