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Fermi Detection of a Luminous γ -ray Pulsar in a Globular Cluster

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We report the Fermi Large Area Telescope detection of γ -ray (>100 megaelectronvolts) pulsations from pulsar J1823–3021A in the globular cluster NGC 6624 with high significance ($\sim 7\sigma$). Its γ -ray luminosity $L_\gamma = (8.4 \pm 1.6) \times 10^{34}$ ergs per second, is the highest observed for any millisecond pulsar (MSP) to date, and it accounts for most of the cluster emission. The non-detection of the cluster in the off-pulse phase implies that it contains < 32 γ -ray MSPs, not ~ 100 as previously estimated. The γ -ray luminosity indicates that the unusually large rate of change of its period is caused by its intrinsic spin-down. This implies that J1823–3021A has the largest magnetic field and is the youngest MSP ever detected, and that such anomalous objects might be forming at rates comparable to those of the more normal MSPs.

Since its launch in 2008, the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope (*F*) has detected whole populations of objects previously unseen in the γ -ray band. These include globular clusters (GCs), which are ancient spherical groups of \sim

19 10^5 stars held together by their mutual gravity. As a class, their γ -ray spectra show evidence
20 for an exponential cut-off at high energies (2, 3), a characteristic signature of magnetospheric
21 pulsar emission. This is not surprising because radio surveys have shown that GCs contain
22 large numbers of pulsars (4), neutron stars that emit radio and in some cases X-ray and γ -ray
23 pulsations.

24 The first GC detected at γ -ray energies was 47 Tucanae (5), soon followed by Terzan 5 (6)
25 and nine others (2, 3). Even so, no individual pulsars in these clusters were firmly identified
26 in γ -rays (7). GCs are more distant than most γ -ray pulsars observed in the Galactic disk (8),
27 thus most pulsars in them should be too faint to be detected individually. The Fermi LAT lacks
28 the spatial resolution required to resolve the pulsars in GCs, which tend to congregate within
29 the inner arcminute of the cluster. Hence, γ -ray photons emitted by all pulsars in a given GC
30 increase the photon background in the folded γ -ray profiles of each individual pulsar in that
31 cluster.

32 One of the GCs detected at γ -ray energies is NGC 6624 (3), located at a distance $d =$
33 8.4 ± 0.6 kpc from Earth (9). With a radio flux density at 400 MHz of $S_{400} = 16$ mJy (10),
34 J1823–3021A is the brightest of the six pulsars known in the cluster. It has been regularly
35 timed with the Jodrell Bank and Parkes radio telescopes since discovery, and with the Nançay
36 radio telescope since the launch of the Fermi satellite. The resulting radio ephemeris (Table
37 S1) describes the measured pulse times of arrival very well for the whole length of the Fermi
38 mission, the root mean square of the timing residuals being 0.1% of the pulsar rotational period.

39 Thus we can confidently use it to assign a pulsar spin phase ϕ to every γ -ray (>0.1 GeV)
40 photon arriving at the Fermi-LAT from the direction (within 0.8°) of the pulsar. We selected
41 photons that occurred between 4 August 2008 and 4 October 2010 that pass the “Pass 6 diffuse”
42 γ -ray selection cuts (1). The resulting pulsed γ -ray signal (above 0.1 GeV, Fig. 1) is very robust,
43 with an H-test value of 64 (11) corresponding to 6.8σ significance. The data are well modeled

44 by a power law with spectral index 1.4 ± 0.3 and an exponential cutoff at an energy of $1.3 \pm$
 45 0.6 GeV, typical of the values found for other γ -ray pulsars [see supporting online material
 46 (SOM)]. The two peaks are aligned, within uncertainties, with the two main radio components
 47 at spin phases $\phi_1 = 0.01 \pm 0.01$ and $\phi_2 = 0.64 \pm 0.01$ (Fig. 1).

48 The pulsed flux above 0.1 GeV, averaged over time, is $F_\gamma = (1.1 \pm 0.1 \pm 0.2) \times 10^{-11}$ erg cm $^{-2}$ s $^{-1}$,
 49 where the first errors are statistical and the second are systematic (SOM). The large distance
 50 of NGC 6624 implies that J1823–3021A is one of the most distant γ -ray pulsars detected
 51 (8). This makes it the most luminous γ -ray MSP to date (12): Its total emitted power is
 52 $L_\gamma = 4\pi d^2 f_\Omega F_\gamma = (8.4 \pm 1.6 \pm 1.5) \times 10^{34} (f_\Omega/0.9)$ erg s $^{-1}$. We obtained the statistical un-
 53 certainty by adding the uncertainties of d and F_γ in quadrature. The term f_Ω is the power per
 54 unit surface across the whole sky divided by power per unit surface received at Earth’s location;
 55 detailed modeling of the γ and radio light curves provides a best fit centered at 0.9, but with a
 56 possible range from 0.3 to 1.8 (SOM).

57 The LAT image of the region around NGC 6624 during the on-pulse interval ($0.60 < \phi <$
 58 0.67 and $0.90 < \phi < 1.07$) shows a bright and isolated γ -ray source that is consistent with the
 59 location of J1823–3021A (Fig. 2); in the off-pulse region ($0.07 < \phi < 0.60$ and $0.67 < \phi <$
 60 0.90) no point sources in the energy band 0.1 - 100 GeV are detectable. Assuming a typical
 61 pulsar spectrum with a spectral index of 1.5 and a cut-off energy of 3 GeV, we derived, after
 62 scaling to the full pulse phase, a 95% confidence level upper limit on the point source energy
 63 flux of 5.5×10^{-12} erg cm $^{-2}$ s $^{-1}$. Thus, J1823–3021A dominates the total γ -ray emission of
 64 the cluster. The combined emission of all other MSPs in the cluster plus any off-pulse emission
 65 from J1823–3021A is not detectable with present sensitivity. No other pulsars are detected in
 66 a pulsation search either.

67 Under the assumption that the γ -ray emission originates from NGC 6624, (3) estimated the
 68 total number of MSPs to be $N_{\text{MSP}} = 103_{-46}^{+104}$. Assuming an average γ -ray luminosity for each

69 MSP (5, 2), similar to the approximation made by (3), our off-pulse flux upper limit implies that
70 $N_{\text{MSP}} < 32$. This is consistent with the estimate $N_{\text{MSP}} = 30 \pm 15$ derived from the correlation
71 between γ -ray luminosity and encounter rate (2). Clearly, the MSP number estimate of (3) is
72 skewed by the presence of a single bright pulsar contributing disproportionately to its emission
73 (13). The off-pulse emission limits can also be used to constrain alternative models for the γ -ray
74 emission from globular clusters, like those invoking inverse Compton (IC) radiation (14, 15).

75 The spin period of J1823–3021A, 5.44 ms, is typical of MSPs. However, its rate of change
76 $\dot{P}_{\text{obs}} = +3.38 \times 10^{-18} \text{ s s}^{-1}$ is one to two orders of magnitude larger than for other MSPs with
77 the exception of J1824–2452A, a pulsar in the GC M28 (16) that has a similarly large \dot{P}_{obs} (17).
78 A possible explanation is that \dot{P}_{obs} is due mostly to the changing Doppler shift caused by the
79 pulsar’s acceleration in the gravitational field of the cluster along the line of sight (a_l):

$$\left(\frac{\dot{P}_{\text{obs}}}{P}\right) = \left(\frac{\dot{P}}{P}\right) + \frac{a_l}{c}. \quad (1)$$

80 If the globular cluster has a reliable mass model, we could use it to estimate lower and upper
81 limits for a_l and estimate upper and lower limits for \dot{P} (18). For NGC 6624 the collapsed nature
82 of its core precludes the derivation of a reliable mass model. Furthermore, radio timing (Table
83 S1) shows that J1823–3021A is only $0'.4 \pm 0'.1$ (a projected distance of 0.018 ± 0.004 pc)
84 from the center of the cluster (19), where the values of a_l can be largest. For this reason, it
85 has been suggested (10) that J1823–3021A is a “normal” MSP (i.e., with small \dot{P}); its large
86 \dot{P}_{obs} being due to its acceleration in the cluster. This conclusion was apparently strengthened
87 by the detection of a second derivative of the spin period $\ddot{P} = -1.7 \times 10^{-29} \text{ s}^{-1}$ (20). This
88 could originate in a time variation of a_l resulting from interaction with a nearby object (21). If
89 sustained it would reverse the sign of \dot{P}_{obs} in ~ 6000 years; suggesting again that the large \dot{P}_{obs}
90 is not only due to dynamical effects, but is possibly a transient feature.

91 However, the total observed γ -ray emission L_γ must represent a fraction $\eta < 1$ of the

92 available rotational energy loss, $\dot{E} = 4\pi^2 I \dot{P} / P^3$, where I is the pulsar's moment of inertia.
 93 Although I depends on the unknown mass of the pulsar and the unknown equation of state for
 94 dense matter, the standard assumption $I = 10^{45} \text{ g cm}^2$ is a reasonable value for a $1.4 M_\odot$ (mass
 95 of the Sun) neutron star. This implies $\dot{P} > 3.4 \times 10^{-19} (f_\Omega/0.9)(I/10^{45} \text{ g cm}^2)^{-1} \text{ s s}^{-1}$. Thus
 96 even an unrealistic γ -ray efficiency $\eta = 1$ would imply that \dot{P} is already $\sim 10\%$ of \dot{P}_{obs} . If we
 97 assume instead $\dot{P} \simeq \dot{P}_{\text{obs}}$, then $\dot{E} = 8.3 \times 10^{35} \text{ erg s}^{-1}$ and $\eta = 0.1 \times (f_\Omega/0.9)(I/10^{45} \text{ g cm}^2)^{-1}$.
 98 Comparison with the observed γ -ray efficiencies of other MSPs (12, 8) shows this to be a more
 99 reasonable range of values; $\eta \sim 0.1$ also represents the upper limit derived for the average effi-
 100 ciency of MSPs in 47 Tucanae (5). Therefore, our γ -ray detection of J1823–3021A indicates
 101 that it is unusually energetic and that most of \dot{P}_{obs} is due to its intrinsic spin-down. The pulsar
 102 has other features that suggest it is indeed unusually energetic: Its alignment of radio and γ -ray
 103 profiles has previously only been observed for the Crab pulsar (22) and three fast, energetic
 104 MSPs: J1939+2134 (the first MSP to be discovered), J1959+2048 (23) and J0034–0534 (24).
 105 Like some of these energetic pulsars and PSR J1824–2452A, J1823–3021A emits giant radio
 106 pulses (25) and has a high 400 MHz radio luminosity of $L_{400} \simeq 1.1 \text{ Jy kpc}^2$ (10), the third
 107 highest among known MSPs. However the correlation between \dot{E} and radio luminosity is far
 108 from perfect given the uncertainties in the distance estimates, moment of inertia, beaming ef-
 109 fects and possibly intrinsic variations of the emission efficiencies. Finally, J1939+2134 also has
 110 a large \ddot{P} (26), which is thought to be caused by timing noise (TN), which scales roughly with
 111 $P^{-1.1} \dot{P}$ (27). In the case of J1823–3021A, if $\dot{P} \simeq \dot{P}_{\text{obs}}$, then TN should be one order of mag-
 112 nitude larger than for J1939+2134; instead its \ddot{P} is $\sim 1.5 \times 10^2$ larger than that of J1939+2134.
 113 This is possible given the observed scatter around the TN scaling law. Thus TN might account
 114 for the \ddot{P} of J1823–3021A, but this is far more likely if $\dot{P} \simeq \dot{P}_{\text{obs}}$.

115 If $\dot{P} \simeq \dot{P}_{\text{obs}}$, we can estimate the strength of its surface dipole magnetic field: $B_0 = 3.2 \times$
 116 $10^{19} \text{ G} \sqrt{\dot{P} P (I/10^{45} \text{ g cm}^2) (R/10 \text{ km})^{-3}} \simeq 4.3 \times 10^9 \text{ G}$ (28) [where R is the neutron star (NS)

117 radius, generally assumed to be 10 km]. MSPs are thought to start as normal NSs with $B_0 \sim$
 118 10^{11-13} G which are then spun up by the accretion of matter and angular momentum from a
 119 companion star. This process is thought to decrease their magnetic field to $B_0 \sim 10^{7-9}$ G; but
 120 the exact mechanism responsible for this is currently not well understood. Our value of B_0
 121 shows that for J1823–3021A this decrease was not as pronounced as for other MSPs.

122 As accretion spins up the NS, it eventually reaches an equilibrium spin period (29) given
 123 by:

$$P_{\text{init}} = 2.4\text{ms} \left(\frac{B_0}{10^9\text{G}} \right)^{6/7} \left(\frac{M}{M_\odot} \right)^{-5/7} \left(\frac{R}{10^4\text{m}} \right)^{18/7} \left(\frac{\dot{M}}{\dot{M}_{\text{Edd}}} \right)^{-3/7}, \quad (2)$$

124 where M is the NS mass, \dot{M} is the accretion rate and \dot{M}_{Edd} is the maximum possible stable ac-
 125 cretion rate for a spherical configuration (known as the Eddington rate). Beyond this, the pres-
 126 sure of accretion-related radiation starts preventing further accretion. After accretion ceases,
 127 the newly formed radio MSP will have P_{init} as its initial spin period. Assuming $\dot{M} = \dot{M}_{\text{Edd}}$,
 128 $M = 1.4 M_\odot$ and $R = 10$ km (as in our estimates of B_0), we obtain $P_{\text{init}} = 1.9 \text{ ms}(B_0/10^9\text{G})^{6/7}$.
 129 For the value of B_0 calculated above, we get $P_{\text{init}} = 6.6$ ms; that is, even if accretion had
 130 proceeded at the Eddington rate, the pulsar would not have been spun up to its present spin
 131 frequency. This is also the case for the other such “anomalous” MSP, J1824–2452A (17); for
 132 all others we have $P > P_{\text{init}}$. A possible explanation is that for these two objects M and I
 133 do not correspond to the assumptions above. If, for example, $\eta = 0.15$, $M = 1.8 M_\odot$ and
 134 $I = 1.8 \times 10^{45} \text{ g cm}^2$ (30) we obtain $B_0 = 3.6 \times 10^9$ G and $P_{\text{init}} = 4.7$ ms. A second possibil-
 135 ity, suggested by eq. 2, is super-Eddington accretion (more precisely, $\dot{M} > 1.6 \dot{M}_{\text{Edd}}$); this can
 136 happen for non-spherical mass accretion. A third possibility is that the value of B_0 was smaller
 137 during accretion (resulting in a smaller P_{init}), and that B_0 has increased since then. This has
 138 been observed for some normal pulsars (31); however there is no evidence of such behavior for
 139 any other MSPs.

140 In any case, the conclusion that $\dot{P} \simeq \dot{P}_{\text{obs}}$ implies a characteristic age $\tau_c = P/(2\dot{P}) = 25$
141 million years. This is likely an over-estimate of the true age of the pulsar, particularly given
142 that P_{init} is likely to be similar to P . Thus J1823–3021A is likely to be the youngest MSP ever
143 detected; only J1824–2452A might have a comparable age. Because of their large \dot{P} s both
144 objects will be observable as MSPs for a time that is $\sim 10^2$ shorter than the ~ 100 “normal”
145 radio-bright MSPs known in GCs. Statistically, this suggests that, at least in GCs, anomalous
146 high B -field MSPs like J1823–3021A and J1824–2452A are forming at rates comparable to
147 those of the more “normal”, radio-bright MSPs.

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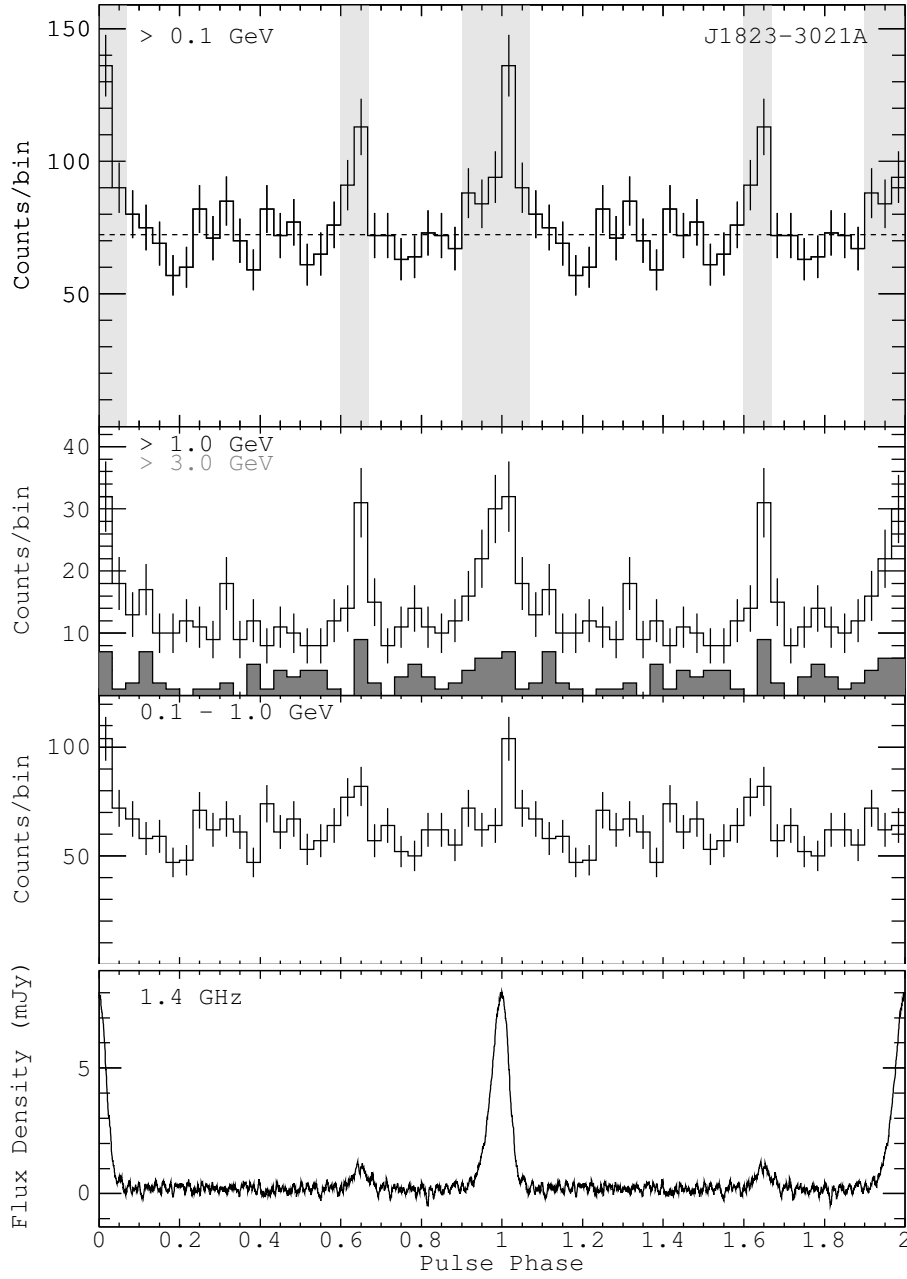


Figure 1: Phase-aligned radio and γ -ray profiles for J1823–3021A. (Bottom) Nançay 1.4 GHz radio profile. (Top and middle) γ -ray profiles obtained with the Fermi-LAT in different energy bands. The dark histogram is for events with $E > 3.0\text{GeV}$. The γ -ray background for the 0.1 GeV light curve was estimated from a surrounding ring, and it is indicated by the dashed horizontal line in the top panel. The highlighted area there shows the on-pulse region selection.

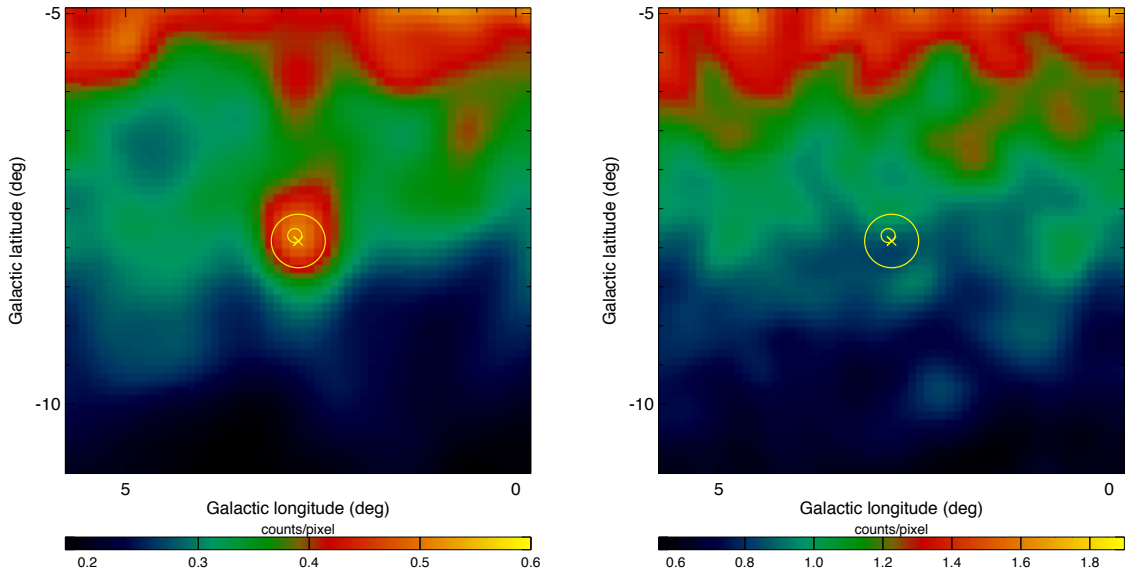


Figure 2: Fermi LAT γ -ray count map above 100 MeV for J1823–3021A during the on-pulse (Left) and off-pulse (Right) regions, as defined in Fig. 1. The 6° by 6° region is centered on the pulsar position (cross). The map was adaptively smoothed by imposing minimum signal-to-noises ratios of 13 and 16 for the on- and off-pulse regions, respectively. The large circle indicates the tidal radius of NGC 6624. The small circle shows the 99% confidence region for the location of the γ -ray source.

327 **Supporting Online Material**

328 **Observations and data analysis**

329 **Radio Timing analysis**

330 With the express purpose of supporting the Fermi mission (33), J1823–3021A is observed
331 approximately 3 times per month with the 76-m Lovell telescope (34), using a 64 MHz band
332 centered at 1404 MHz connected to an analog filterbank. Since mid-2009 observations have also
333 been performed using a digital filterbank backend with 1024×0.5 MHz channels of which ap-
334 proximately 250 MHz is used. Highly precise timing measurements are also conducted with the
335 Nançay radio telescope (35). These have included regular observations of J1823–3021A since
336 mid-2006. Approximately every two months, the pulsar is observed for 1 hour at 1.4 GHz.
337 A 128 MHz bandwidth is coherently dedispersed using powerful GPUs (Graphics Processing
338 Units). A total of 104 pulse times of arrival (TOAs) were obtained from the two telescopes
339 between mid-2006 and mid-2010. The TEMPO2 timing package (36) was used to build the
340 timing solution, which includes the pulsar rotation frequency and its derivatives, the dispersion
341 measure, and the pulsar position. The post-fit residuals are characterized by a weighted rms of
342 $7.3 \mu\text{s}$. The resulting parameters are summarized in Table S1. No trends are noticeable in the
343 post-fit residuals.

344 **Fermi LAT data analysis**

345 We have observed J1823–3021A with the Large Area Telescope aboard Fermi from 2008 Au-
346 gust 4, when the satellite began scanning-mode operations, to the end of the validity range of the
347 pulsar radio ephemeris (2010 October 14). The data analysis presented in this paper has been
348 performed using the LAT Science Tools package 09-21-00 and the P6 V3 Diffuse instrument
349 response functions (IRFs). Events tagged “Pass 6 diffuse” having the highest probability of

350 being γ -ray photons (37) and coming from zenith angles $< 100^\circ$ (to reject atmospheric γ -rays
351 from the Earth’s limb) were used. Additionally, a rotational phase was assigned to each selected
352 LAT event using the radio ephemeris as an input to the Fermi plugin (38) distributed with the
353 TEMPO2 pulsar timing software.

354 Using the `pyLikelihood` likelihood fitting tool with the `NewMinuit` optimizer, we per-
355 formed a binned spectral analysis to determine the energy flux and the spectral shape of the
356 source. Events in the range 0.1–100 GeV were extracted from a $20^\circ \times 20^\circ$ square region of in-
357 terest (ROI) centered on the pulsar position. To reduce the effect of the Earth’s atmospheric
358 emission, the time intervals when the Earth was appreciably within the field of view (specifi-
359 cally, when the center of the field of view was more than 52° from the zenith) were excluded
360 from this analysis. The Galactic diffuse emission was modeled using the *gll_iem_v02* map cube,
361 while the extragalactic emission and residual instrument backgrounds were modeled jointly by
362 the isotropic component *isotropic_iem_v02*. These two models are available from the Fermi
363 Science Support Center¹. In addition, all the sources found in an internal catalog based on 18
364 months of data (similar to (39)) above the background with significances $> 5\sigma$ and within 20°
365 from the pulsar were included in the model. Sources were modeled with a power law spectrum,
366 except for pulsars for which a power law with an exponential cut-off was used (40). Sources
367 more than 5° from the pulsar were assigned fixed spectra taken from the source catalog. Spectral
368 parameters for sources within 5° of the pulsar were left free for the analysis.

369 The pulsar location at the core of NGC 6624 is located just outside the 99% statistical
370 error contour of the γ -ray source 1FGL J1823.4–3009 (39), based on an analysis of the first
371 11 months of the LAT survey data. Therefore, (41) did not establish an association between
372 1FGL J1823.4–3009 and the globular cluster. (42), using a larger dataset, showed that the
373 γ -ray position lies within the (20.55′) tidal radius of the cluster. To check the association,

¹<http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

374 we first reevaluated the position of the γ -ray source 1FGL J1823.4–3009, using the on-pulse
 375 ($0.60 < \phi < 0.67$ and $0.90 < \phi < 0.07$) segment of the pulsar rotational phase (to improve
 376 the signal-to-noise ratio), to be ($\alpha_{2000} = 275.87^\circ$, $\delta_{2000} = -30.29^\circ$) with a 99% confidence
 377 error radius of 0.09° . This places the pulsar radio position just inside the 99% error contour
 378 of the γ -ray source. We also investigated the off-pulse window and detected a $\sim 4\sigma$ point
 379 source which coincides with the position of the radio source NVSS J182324–300311 ($\alpha_{2000} =$
 380 275.8515° , $\delta_{2000} = -30.053278^\circ$). The signal, only observed during the first year of the Fermi
 381 mission, is located 0.11° away from the position of 1FGL J1823.4–3009 and 0.31° away from
 382 NGC 6624. It is likely that 1FGL J1823.4–3009, located between NVSS J182324–300311 and
 383 NGC 6624, includes contributions from both of these sources. Using the second year of data,
 384 when the nearby faint source is off, we localize the γ -ray source corresponding to the pulsar to
 385 ($\alpha_{2000} = 275.93^\circ$, $\delta_{2000} = -30.34^\circ$) with a 68% error counter radius of 0.07° . This position is
 386 consistent with the radio pulsar position. We then fitted the spectrum of the pulsar at the radio
 387 pulsar position using a power law with an exponential cut-off. Figure S1 shows both the fit
 388 between 0.1 and 30 GeV (solid lines) and the spectral points derived from likelihood fits to each
 389 individual energy band in which it was assumed the pulsar had a power-law spectrum.

390 **Light Curve Modeling**

391 There have been two major contenders for modeling the high-energy (HE) radiation (roughly
 392 100 MeV to 10 GeV range) from pulsars, those which assume that the observed γ -rays are emit-
 393 ted near the stellar surface (43, 44) above the magnetic polar cap and those which assume the
 394 γ -rays originate primarily in the outer magnetosphere near the light cylinder (the distance from
 395 the rotation axis $\vec{\Omega}$ at which the co-rotation equals the speed of light). Both classes of models
 396 assume that the HE γ -rays are curvature radiation from highly-relativistic electrons/positrons in
 397 the radiation-reaction regime. The two most common outer-magnetospheric emission models

398 are the outer gap (OG; (45, 46, 47)) and the slot gap (48) models. For our purposes we took the
 399 two-pole caustic (TPC; (49)) model to be a geometric realization of the slot gap. TPC and OG
 400 models both assume that the emitting electrons are accelerated up to high altitudes in narrow
 401 gaps along the last-open field lines. The OG model only allows acceleration above the null-
 402 charge surface (NCS; where $\vec{\Omega} \cdot \vec{B} = 0$) whereas in the TPC model electrons are accelerated
 403 from the stellar surface. The HE pulse profiles in these outer-magnetospheric models are the re-
 404 sult of the accumulation of photons in narrow phase bands due to a combination of three effects:
 405 aberration (change of photon direction due to the high corotation velocity), time-of-flight de-
 406 lays (photons produced at higher altitudes will reach an observer earlier than those coming from
 407 lower altitudes), as well as the magnetic field line curvature (photons are assumed to be created
 408 tangential to the local magnetic field line in the corotating frame, and their direction is therefore
 409 very sensitive to the magnetic field geometry). This is referred to as caustic emission (50).

410 TPC and OG models are generally used in conjunction with a low-altitude radio cone beam
 411 geometry (e.g., (51, 52)). Due to the difference in altitude of the radio and γ -ray emission, there
 412 will be a phase lag between the radio and γ -ray profiles. Polar-cap (e.g., (44)) γ -ray emission
 413 models do predict much smaller phase lags but, due to the large open field line region of MSPs,
 414 they cannot produce the narrow peaks observed in the γ -ray light curve of PSR J1823–3021A.
 415 The phase-alignment of PSR J1823–3021A’s radio and γ -ray light curves argues for overlap-
 416 ping γ -ray and radio emission regions. To reproduce the phase-aligned light curves we used
 417 altitude-limited versions of the TPC and OG models (aTPC and aLOG, respectively) which
 418 were first introduced to model the light curves of the MSP PSR J0034–0534 (53). These are
 419 very similar to the standard TPC and OG models, except that the minimum and maximum radii
 420 of the radio emission region as well as the maximum radius of the γ -ray emission region are free
 421 parameters (the minimum γ -ray emission radius being set by the standard models). Therefore,
 422 both radio and γ -ray photons originate in a TPC or OG-like structure, with a significant amount

423 of overlap between the two emitting regions leading to phase-aligned profiles. This implies
 424 that the radio emission is also caustic in nature, supported by polarimetric observations which
 425 find 0% linear polarization for PSR J1823–3021A (54). Conversely, these models provide a
 426 framework to constrain the respective radio and γ -ray emission geometries when comparing the
 427 model light curves to the data.

428 We have simulated γ -ray and radio light curves using alTPC and aLOG models with a spin
 429 period $P = 1.5$ ms, steps of 1° in magnetic inclination angle (α) and viewing angle (ζ), 0.05
 430 in accelerating emission layer width (w , normalized to the opening angle of the polar cap),
 431 and 0.10 (in units of $R_{LC} = cP/(2\pi)$) for the emission altitudes. The spin period used in
 432 the simulation is less than that of PSR J1823–3021A (5.44 ms) but this quantity enters the
 433 simulation mainly through the size of the polar cap. Using models with a shorter period will, at
 434 most, overestimate any predicted off-pulse region. We have developed a Markov chain Monte
 435 Carlo (MCMC) maximum likelihood technique to jointly fit the γ -ray and radio profiles and
 436 pick the best-fit parameters (55). We fit the ≥ 500 MeV γ -ray light curve in 60 bins and rebinned
 437 the radio profile to 60 bins. For the γ -ray models the minimum emission altitudes (R_{min}^γ) were
 438 specified as described previously while the maximum emission altitudes were allowed to be free
 439 under the constraint $R_{max}^\gamma \geq 0.7 R_{LC}$. The radio emission altitudes are unconstrained save that
 440 $R_{max}^R > R_{min}^R$. The best-fit parameters for both models are given in Table S2; the likelihood
 441 does not prefer one model over another. The alTPC model has best-fit gap widths of 0.0. This
 442 is unphysical and should be taken to indicate that the true gap widths are between 0.0 and
 443 0.05. Following (52) we can estimate the beaming factor (f_Ω) for both models using Eq. 4
 444 of (51), see Table S2. Presently we are unable to provide reliable uncertainty estimates for our
 445 model predictions and, thus, can not propagate any uncertainty on f_Ω into the uncertainty on
 446 L_γ . However, while PSR J1823–3021A stands out in some respects, the shape of the observed
 447 HE light curve is very typical of known γ -ray MSPs. The best-fit geometries of (55) to these

448 MSPs yield values of f_Ω from approximately 0.3 to 1.8, with mean of 0.81 and rms of 0.36. We
449 therefore expect the f_Ω value for J1823–3021A to be similar to the geometries which, in these
450 models, produce “typical” γ -ray light curves. The high and low tails of this distribution suggest
451 that the γ -ray efficiency could reasonably be anywhere from 3 to 20% but neither extreme
452 affects the conclusion of the main text that most of the observed \dot{P} is intrinsic to the pulsar.

| Timing parameters | |
|--|---|
| Right Ascension, α (J2000) | 18 ^h 23 ^m 40 ^s .48466(4) |
| Declination, δ (J2000) | −30° 21′ 39″.988(4) |
| Solar System Ephemeris | DE 405 |
| Reference time scale | TDB |
| Reference time (MJD) | 54939 |
| Spin Frequency, ν (Hz) | 183.823389814514(7) |
| First derivative of ν , $\dot{\nu}$ (10^{-15} Hz s ^{−1}) .. | −114.1351(4) |
| Second derivative of ν , $\ddot{\nu}$ (10^{-25} Hz s ^{−2}) | 5.8(1) |
| Dispersion Measure, DM (cm ^{−3} pc) | 86.864(9) |
| Validity Range (MJD) | 53773.35 – 55483.67 |
| RMS Timing Residuals (μ s) | 7.3 |

Table S1. Timing parameters for J1823–3021A. The center of the globular cluster is located at $\alpha = 18^{\text{h}}23^{\text{m}}40^{\text{s}}:51 \pm 0^{\text{s}}:008$, $\delta = -30^{\circ}21'39''.7 \pm 0''.1$.

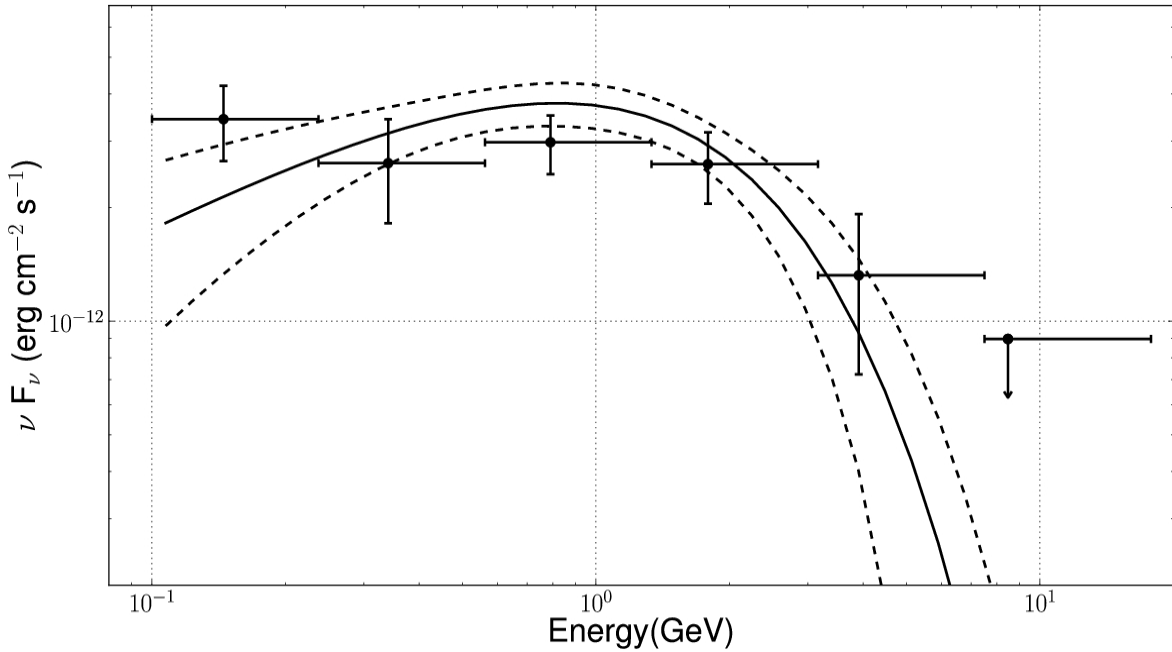


Fig. S1. γ -ray spectral energy distribution of J1823–3021A obtained with the Fermi Large Area Telescope. The solid black line shows the maximum likelihood fit to a power law with exponential cut-off. The dashed lines are $\pm 1\sigma$ uncertainties on the fit parameters. Plotted points are from likelihood fits to individual energy bands with $> 3\sigma$ detection above background for two degrees of freedom, otherwise a 95% confidence level upper limit arrow is shown. The errors are statistical only.

| Best-fit Light Curve Parameters | | | | | | | | | | |
|--|----------------------|--------------|-------------------------|------------------------|--------|--------------|----------------|--------------------|------------------------------|----------------------|
| Model | $-\log(\text{Like})$ | f_{Ω} | α ($^{\circ}$) | ζ ($^{\circ}$) | Φ | w_{γ} | w_{R} | R_{max}^{γ} | R_{min}^{R} | R_{max}^{R} |
| aTPC | 173.8 | 0.9 | 51 | 68 | 0.017 | 0.00 | 0.00 | 1.0 | 0.2 | 0.9 |
| aIOG | 173.6 | 0.9 | 69 | 68 | 0.017 | 0.05 | 0.10 | 1.2 | $max\{R_{\text{NCS}}, 0.2\}$ | 0.8 |

Table S2. Results of MCMC maximum likelihood fits to the γ -ray and radio light curves of PSR J1823–3021A using the aTPC and aIOG models.

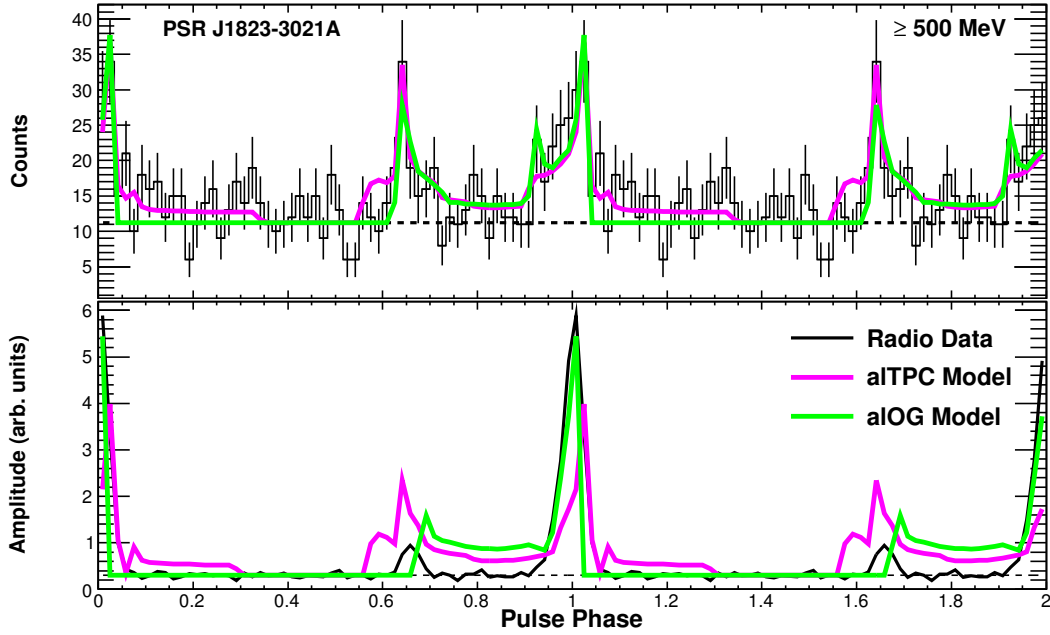


Fig. S2. Observed and best-fit γ -ray (top) and radio (bottom) light curves for PSR J1823–3021A using the aITPC (pink) and aLOG (green) models described in the text. The dashed, horizontal lines in both panels correspond to the estimated background levels. The γ -ray background was estimated using an annular ring centered on the radio position with inner and outer radii of 1° and 2° , respectively. The radio background was estimated by fitting the region between 0.1 and 0.6 in phase to a constant value. The parameters of the best-fit light curves are given in Table S2.