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Title	Radio pulsations from a neutron star within the gamma-ray binary LS I +61° 303
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The fact that the pulsations are not present in three out of four observations (a couple of them very close to one another) reveals a rapid change of conditions either in the interstellar medium between us and the source, the neutron star environment, or the neutron star itself.

Interstellar scintillation may be produced by a diffractive scattering medium along our line of sight, for which the typical timescale²⁹ is $\Delta t_d = 2.53 \times 10^4 (D \Delta \nu_d)^{1/2} / (\nu V_{\text{ISS}})$ s, where D the distance to the source in kpc, $\Delta \nu_d$ the decorrelation bandwidth in MHz, ν the observed frequency in GHz and V_{ISS} the velocity of interstellar scintillation (ISS) diffraction pattern in km s^{-1} (which in binaries is typically dominated by pulsar velocities, in the range of few tens to few hundreds km s^{-1}). For the observation shown in Figure 1, scintillation could explain changes in flux up to a few minutes, but not the several hours, in consecutive days, when pulsations are absent. And this does not consider that the bandwidth of the observation is larger than the decorrelation bandwidth and therefore scintillation would be averaged out. Refractive scintillation, on the other hand, could have a longer timescale and we cannot rule it out a priori, although the flux modulation we have seen would be larger than expected³⁰.

A second possibility is that the flux modulation is related to an intrinsic nulling of the pulsar, a temporary broadband cessation of normal pulsar emission likely produced by magnetospheric changes. About 8% of the known pulsars exhibit nulling³¹, with durations that go from a single pulse to several days. Some pulsars actually live most of the time in their null state, to activate themselves only for short periods, making them difficult to detect. Mode changing is a related phenomenon where the mean pulse profile abruptly changes in a matter of minutes to come back to the original later on (see, e.g.,³²). With the current lack of information regarding pulsations at other frequencies, associating the absence of pulsations we observe to nulling or mode changing is not possible. The fairly rapid spin period, and the plausibly low age of LS I +61° 303 (see e.g.,¹), may argue against these interpretations. Nulling appears predominantly for longer-period and older pulsars. It is interesting, in the same context, to note the similarity of the phenomenology seen to those of rotating radio transients, pulsars which sporadically emit single pulse outbursts instead of continuous pulse trains³³.

Finally, changes in the wind properties can easily affect the pulsed signal. And as the Be stellar wind is likely to be clumpy, it would be impossible to predict the absorption level that any radio signal will be subject to in a local basis (see the discussion in e.g.²⁵). Then, the transient behaviour could plausibly be interpreted as a result of the rapid change in the environmental conditions. Regarding this possibility, it might be useful to compare with the case of the pulsar-

composed gamma-ray binary PSR B1259-63. Despite this system has a much larger orbit, radio flux variations at a time scale of minutes to hours were also reported in PSR B1259-63, together with changes in the local properties of the Be star wind/disk encountered by the pulsar (see e.g.,³⁴ and references therein). It is reasonable to expect these same effects apply to LS I +61° 303, enhanced due to the smaller spatial scale of the system.

We can also draw some phenomenological connections with transitional pulsars. These are redback systems, a millisecond pulsar in a close orbit with a low-mass companion star. These systems can exhibit highly variable eclipses from orbit to orbit, radio variability, X-ray/radio anti-correlation, and some also fully disappear in radio for days (see, e.g.,³⁵). Whereas LS I +61° 303 is not a redback pulsar, similarly to them, it does have a non-compact stellar companion which fills the system with ionized gas. The variability of the pulsations could likely be due to the latter, and the pulsed signal can also be affected by matter-magnetosphere interaction. Future simultaneous campaigns in X-rays and radio may shed further light on this comparison.

In any case, our finding suggests that LS I +61° 303 is a pulsar-composed system and place the tight constraint on pulsar-based models when explaining its multifrequency phenomenology. Among them, models based in state transitions might be appealing: A study in the context of the short magnetar-like flares and the superorbital variability allowed to define a preferred pulsar period for LS I +61° 303 of 0.26 s (see figure 4 of Ref.³⁶), as we find here. With the knowledge gained from our observational finding, this and other pulsar- based models can be revisited and enhanced, and applied to the search and characterization of pulsations at all frequencies.

Table 1: Log of observations

Mid of observation time	Orbital phase	Exposure Time/h	Sampling Time/ μ s	Pulse detected	$S_{\text{mean}}/S_{\text{UL}}/\mu\text{Jy}$
58,788.7257	0.07	2.2	98.304	No	-/1.61
58,855.5278	0.59	3.0	98.304	Yes	4.40/1.37
59,093.8646	0.58	3.0	196.608	No	-/1.37
59,094.8681	0.62	2.0	196.608	No	-/1.68

The orbital phases are calculated with the radio ephemeris given in Ref.³.

Methods

FAST observations

FAST is the most sensitive operating radio telescope^{37,38}, and it has recently been used to detect some very faint pulsars^{39–41}. LS I +61° 303 was observed by *FAST* four times in 2019–2020, and all data were equally processed with the packages available in PRESTO using the following usual steps²⁷: 1. We masked and zapped the radio-frequency interference (RFI) using the routine `rfifind`; 2. After RFI excision, the data were de-dispersed with the trial DMs between 0 and 500 pc cm⁻³ by using the routine `prepsubband`; 3. For the resulting de-dispersed time series, we carried out a blind Fourier-domain acceleration periodicity search with the routine `realfft` and `accelsearch`, yielding the periodic candidates. 4. The periodic candidates were further sifted with the routine `ACCEL_sift.py`. 5. The data were corrected to Solar System Barycentre and were automatically folded over all derived periodic candidates and possible period-derivatives using the routine `prepfold`. We could then check and confirm the signal by diagnosing the folding plots. That is, the precise values of DM, P , \dot{P} and their uncertainties were obtained by folding the data to reach a maximum χ^2 (i.e. SNR).

The pulsations were only detected in the *FAST* data taken on 2021 January 7th, and the folding results with the identified period, $P = 269.15508 \pm 0.00016$ ms¹, are shown in Supplementary Figure 1. We did not find any public pointed observation around 2020 January 7th in multi-wavelength bands. We checked that there was no unusual behavior displayed in survey data, including Swift/BAT, MAXI, and *Fermi*-LAT.

Due to the fact that we are considering only 3 hours of observation spanning a very small orbital phase, we cannot recover the Doppler-shifted signals to determine this pulsar’s intrinsic \dot{P} and \ddot{P} . When carrying out a non-acceleration search with the option “-nopdsearchr” in the routine `prepfold`, we obtain a slightly smaller single-trial significance of $\sim 21.1\sigma$.

An estimate of the mean flux density that each of our observations would have detected, S_{mean} , can be obtained via⁴²:

$$S_{\text{mean}} = \frac{\eta\beta T_{\text{sys}}}{G\sqrt{N_p\Delta\nu T_{\text{int}}}} \sqrt{\frac{W}{P-W}} \quad (1)$$

where η is the SNR threshold, β is the sampling efficiency, T_{sys} is the system temperature, T_{int} is the integration time, and G represents for antenna gain. For *FAST*, $\beta=1$, $T_{\text{sys}}=24$ K, $G=16$ K

¹We made the barycenter correction with the wrong coordinates, and the results given in the Atel #14297 were inaccurate. The results are corrected in this paper.

Jy^{-1} . The bandwidth $\Delta\nu$ is 300 MHz as we masked 100 MHz in our pipeline due to the RFI, and finally, $N_p = 2$ is the number of polarizations, P is the period of pulsar, and W is the width of pulse profile. The value of $W/P=0.1$ (see the figure in the main text) is adopted for LS I +61° 303. The 7σ detection limit ($\alpha=7$) of the flux density for each observation, S_{UL} , is also calculated and listed in Table 1.

In comparison, the Green Bank Telescope (GBT, <https://greenbankobservatory.org/science/telescopes/gbt/>) and the 100-m Effelsberg radio telescope (<https://www.mpifr-bonn.mpg.de/effelsberg/astronomers>) have similar system temperatures, but lower antenna gains, 2 K Jy^{-1} and 1.55 K Jy^{-1} at 1.4 GHz, respectively. That is, the mean pulsed signal reported with *FAST* data ($\sim 4.4 \mu\text{Jy}$, see Table 1) would be unattainable for the GBT and Effelsberg telescopes: an unrealistic integration time of $> 20 - 30$ hours would have been required for a 7σ detection. Alternatively, flux variations, as are evidently displayed in LS I +61° 303 may lead to overpassing the threshold for detection at certain times. According to Equation 1, the estimated pulsed flux of LS I +61° 303 increased up to $12.85 \mu\text{Jy}$ (single-trial significance of 26.7σ) in the last half-hour. Such level of flux might be detected by the GBT and Effelsberg telescopes within a reasonable observational time of ~ 2.2 hours. LS I +61° 303 is too north to be observed by the Arecibo (http://www.naic.edu/science/generalinfo_set.htm).

Single pulse analysis

In addition to PRESTO, we have also used the package BEAR (Burst Emission Automatic Roger)⁴³ to do a single pulse search for all observational data. The RFI of *FAST* are mostly coming from satellites, so the frequency from 1200 MHz to 1240 MHz and 1270 MHz to 1300 MHz were cut off from the data. We de-dispersed the data from 0 pc cm^{-3} to 500 pc cm^{-3} in steps of 0.5 pc cm^{-3} and use a box-car-shaped match filter to search for bursts with width between 0.2 ms and 30 ms. Candidates with a SNR threshold larger than 7 were plotted by BEAR and visually inspected. For our data, the observations performed on MJD 58,788, 59,093 and 59,094 lead to no significant detection in our single pulse searching pipeline. The analysis of the data obtained on MJD 58855 leads to 42 single pulses. Supplementary Figure 2 shows all of the single pulses' dynamic spectra and their profiles. Parameters of all these single pulses are listed in Supplementary Table 1. The DM value for each single pulse ($\text{DM}_{s/n}$) was obtained by aligning the signal across frequency to achieve the best peak SNR⁴⁴. This also explains the apparent variability seen in the DM values, meanwhile the mean value of DM is 240.2 pc cm^{-3} which is consistent with the pulsar mentioned above. We use intensity weighted width (IWW) to measure the burst width by treating the pulse profile as the temporal intensity distribution function, and then calculated the standard deviation of

time. The mean flux density is computed using the following equation, uncertainties are dominated by the system noise temperature ($\sim 20\%$ ³⁸).

$$S_{\text{mean}} = \frac{\text{SNR} \cdot T_{\text{sys}}}{G \sqrt{N_p} T_{\text{sample}} \Delta\nu} \quad (2)$$

We show the folded single pulses data with P and \dot{P} obtained in Supplementary Figure 1, and display their occurrences in the time-phase diagram with the red bars (Supplementary Figure 3).

The non-zero DM value and the variable RFI recorded in the data suggested that the detected pulses are unlikely from the instrumental or terrestrial interference. Plus, the single pulses displayed a dramatic flux variation (by a factor of $> 10^3$, see Supplementary Table 1) in short time scales, while retaining the DM value. Therefore, the detections of both the weak averaged pulse and the energetic single pulses in the same observation cannot be interpreted as instrumental origin or terrestrial interference.

In addition, the detection of energetic single pulses would indicate that the emission is unlikely from the secondary lobes, i.e., emission from a pulsar far away the field of LS I +61° 303 ($\sim 6' - 8'^{45}$). If the emission would come from secondary lobes, the intrinsic flux density should be about ~ 1000 times brighter than the detected level⁴⁵, i.e. about $\sim 10 - 100$ Jy. If so, other telescopes could have easily detected the signal already. While this paper was being reviewed, we made another dozen *FAST* observations, covering the whole orbital phase. The preliminary analysis reveals several single pulses on 2021 November 2nd, corresponding to an orbital phase of ~ 0.69 . These single pulses share similar properties to those reported here in more detail and further support their origin in LS I +61° 303. A detailed analysis on these single pulses will be presented elsewhere.

Pulse No.24 and Pulse No.41 show an exponential-like scattering tail. For these two bursts, we used a Gaussian convolved with a one-sided exponential function to fit them,

$$f(t, \tau) = \frac{S}{2\tau} \exp\left(\frac{\sigma^2}{2\tau^2}\right) \exp\left(-\frac{t - \mu}{\tau}\right) \times \left\{ 1 + \text{erf}\left[\frac{t - (\mu + \sigma^2/\tau)}{\sigma\sqrt{2}}\right] \right\} \quad (3)$$

where S is the flux density of the Gaussian, μ is its center, and σ is its standard deviation. τ is a time constant of the one-sided exponential function. We split the data into 8 evenly spaced sub-bands across the 500 MHz raw bandwidth, then clip the channels RFI. For each sub-band with $\text{SNR} \geq 7$, we integrated the pulse intensities over time and used MCMC to fit the intensity profile with the equation above along the frequency axis (panel B of Supplementary Figures 4 and 5) in order to

get the scattering time scale (σ_{chn}) and the standard deviation (τ_{chn}) of each sub-band (panel C of Supplementary Figures 4 and 5). At each frequency channel, the scattering time scale is

$$\tau_{\text{chn}}(\nu) = \tau_{\text{chn}} \left(\frac{\nu}{\nu_{\text{ref}}} \right)^\alpha \quad (4)$$

where ν_{ref} is the reference frequency and is set to 1 GHz, α is the frequency scaling index. Linear regression of the scattering timescales shows their scattering timescale at 1 GHz of $\tau_{1\text{GHz}}=29.85\pm 4.64$ ms, 15.57 ± 2.39 ms and a frequency scaling index of $\alpha=-2.49\pm 0.53$, and -1.91 ± 0.80 for the two pulses, respectively. The scattering by the ionized plasma leads to the pulse being asymmetrically broader at lower frequencies. For the thin-screen scattering model, we could expect scaling indexes of -4 and -4.4, for Gaussian and Kolmogorov inhomogeneities, respectively^{46,47}. However, note that deviations from the theoretical models had been already reported in several pulsars (e.g. PSR B0823+26, PSR B1839+56, and others): It was suggested that lower α values could result from limitations of the thin-screen model or from an anisotropic scattering mechanism⁴⁸. In our case, the distribution of the ionized plasma around LS I +61° 303 cannot be an infinite thin screen, and should deviate from either Gaussian or Kolmogorov inhomogeneous distribution.

Uncertainties

Except for the orbital period, the other orbital parameters, including the orbital phase of periastron and the eccentricity, still bear relatively large uncertainties. Currently, the orbital period is well-determined as $P \sim 26.4960 \pm 0.0028$ days, see e.g.³. The orbital phase of periastron (ϕ_{peri}), instead, was estimated by fitting the radial velocities to be in the range of 0.23–0.30, and the eccentricity e in the range of 0.55–0.72, e.g.,^{15–17}. Recently, however, Kravtsov et al.⁴⁹ obtained a notably different orbital solution using optical polarization measurements, i.e. a small eccentricity $e < 0.2$, and $\phi_{\text{peri}} \sim 0.6$, although some of their parameters are degenerate. The latter solution, as the authors discuss, is not devoid assumptions that may directly impact on the results. If correct, the solution presented by Kravtsov et al. would imply that notable reassessments are needed when considering, for instance, the orbital location and interpretation of all multifrequency phenomenology of the system, as well its age. However, we advise to keep this uncertainty in mind until a final orbital solution is established beyond doubt. Given that our observations are short in comparison to the orbital period of the binary, and that the pulsation appears to be non-steady in nature, the orbital imprint cannot be constrained with our data.

Finally, we ponder how likely could it be that within this spatial extent, *FAST* is actually detecting a different pulsar lying within the angular resolution (at the L-band) of *FAST*, $\sim 2.9'$ ³⁸. For LS I +61° 303 in particular, a similar issue appeared when analyzing the magnetar-like flares

detected from the same region¹⁰⁻¹². Swift, the X-ray satellite that observed them, had a $\sim 1.4'$ positional uncertainty and no other candidate different from LS I +61° 303 was found. A reanalysis of the flare data, as well as a subsequent 96 ks observations with the *Chandra* X-ray telescope, did not reveal any other candidate in that region either¹³. Neither it did a combined analysis of archive Very Large Array radio data nor near infrared observations¹². These studies concluded that the simplest explanation is that LS I +61° 303 was the origin of the flares.

There are just a few gamma-ray binaries known in the Galaxy (less than 10 in total) and we know already about three thousand radio pulsars⁵⁰, of which about 30 have shown magnetar-flare behavior. If we were to assume that LS I +61° 303 is different from the radio pulsar we detect, and different too from the origin of the magnetar-like flares detected from the same region earlier, we would need to find three relatively rare objects aligned within a few arcmin. To qualitatively assess how likely this is we can consider first that the short bursts and the radio pulsations reported here come from two unrelated neutron stars in the small field of view close to LS I +61° 303. Using the ATNF Pulsar Catalogue (<https://www.atnf.csiro.au/research/pulsar/psrcat/>) as a basis for what we have been able to detect with current instruments, taking all 2072 pulsars within the Galactic latitude of $\pm 10^\circ$ and excluding those in globular clusters, the probability to find two pulsars within $\sim 2.9'$ is $< 7 \times 10^{-6}$. We would still need to multiply this by the probability to find LS I +61° 303 within the same region. Assuming that there are 10 sources like LS I +61° 303, the probability would reduce to $< 1 \times 10^{-11}$. If we were to assume that the system producing the magnetar-like flare and the pulsation we detect are the same, i.e., a single pulsar, but different from LS I +61° 303, the probability to randomly find both a pulsar producing magnetar phenomenology and a gamma-ray binary within $\sim 2.9'$ assuming a uniform distribution in the $\pm 10^\circ$ Galactic plane region, would be $\sim 3 \times 10^{-10}$.

We caveat that these numbers are uncertain, as they lack details regarding spatial distribution of sources being non-uniform or considerations relative to the age the system. The magnetar-behavior, for instance, seems to appear more often at younger pulsar ages, so not all pulsars would equally serve as a counterpart for the flares, see e.g.,⁵¹. These estimations also suffer from biases from incomplete and non-uniform observational samples. The ATNF catalog is a multi-frequency, multi-facility compilation, rather than a complete survey at a fixed sensitivity. Ideally, one would use a complete survey using *FAST* itself to judge the surface density of pulsars specifically at the detected flux density and band. Although this is currently unavailable, simulations³⁹ showed that *FAST* should be able to discover about 1000 pulsars, depending on available observation time. This number is lower than what we have considered above using the whole ATNF catalog and does not change the prior conclusion.

Considering the reverse the problem can be useful: we asked how many pulsars with magnetar behaviour there should be for an alignment with LS I +61° 303 to happen by chance. To do this we can simulate sets of Galactic positions of putative pulsars producing magnetar flares and measure which is the random coincidence between these and our source of interest (so that both sources lie within 3 arcmin). We can do so respecting the spatial distribution of the current population of pulsars in Galactic longitude and latitude. Using 100000 simulated sets (a larger number does not notably change the results), of 1928 magnetars each, the average number of simulated coincidences between the position of one of them and LS I +61° 303 would be ~ 0.00093 (standard deviation 0.0304). In this example, we have taken the actual number of known pulsars with $|b| < 5$ degrees (1928) and considered that future samples will contain such a number of magnetars. This is indeed conservative. For context, this number is a factor of > 60 beyond the magnetars currently known, or a factor of 2 larger than all pulsars expected to be detected anew by *FAST*, or even a factor of 4 larger than the number of magnetars born in the Galaxy in the last 25 kyr assuming the most favorable birth rate⁵². The main conclusion is that although it is formally impossible to rule out that there is a projected superposition of different sources, the combinations of these relatively rare systems in such a small region of the sky appears to be unlikely.

Code availability

PRESTO (<https://www.cv.nrao.edu/~sransom/presto/>)

BEAR (<https://psr.pku.edu.cn/index.php/publications/software/>)

Data Availability The data sets generated during and/or analysed during the current study are available from the authors on reasonable request.

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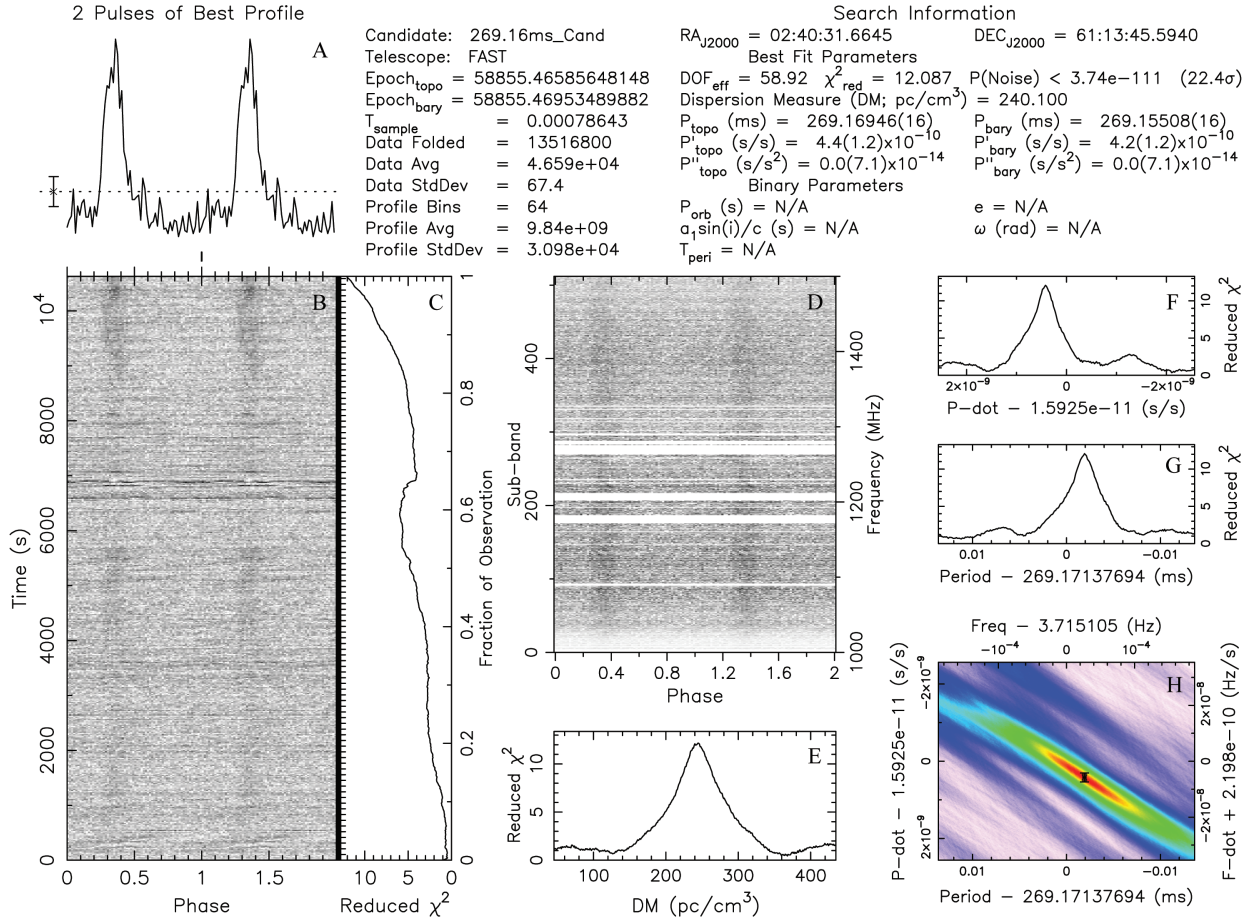
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Author contributions S.S.W., L.Q., and B.J.W. have contributed equally to these results. S.S.W. proposed the observational project. The *FAST* team led by P.J. designed and scheduled the observations during the *FAST* commissioning stage. L.Q. carried out the observations, and B.J.W. analyzed the data. D.F.T., J.L. and A.P. contributed to interpreting the results. D.F.T., S.S.W., B.J.W. wrote the paper. P.J., R.X.X., J.Z.Y., Q.Z.L., M.Y.G., Q.R.Y. participated in the interpretation of the results. All authors discussed the contents of the paper and contributed to the preparation of the manuscript.

Competing Interests The authors declare that they have no competing financial interests.

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Supplementary Information



Supplementary Figure 1: Standard plot of the radio-pulsation search results with the routine `prepfold` in the PRESTO package. The validity of derived parameters can be found in the panels **E-G**, where the χ^2 is a function of DM, P , and \dot{P} , respectively. Meanwhile, the confidence contour of P and \dot{P} is shown in **H**. The averaged pulse profile as a function of observing frequency is shown **D**. Pulse profiles in the left-hand plots are magnified and shown in Figure 1 of the main text.