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Discovery of a radio emitting neutron star with an ultra-long spin period of 76 seconds

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Author contributions M.C. and B.W.S. drafted the manuscript with suggestions from co-authors. M.C. is PI of the MeerKAT DDT and Parkes data. B.W.S. is PI of MeerTRAP and R.F. and P.W. are PIs of the ThunderKAT data. M.C. reduced and analyzed the radio time domain data for quasi-periodicity, and M.C. and M.K. interpreted it. I.H. calibrated, imaged and performed astrometry on the data to localize the source. B.W.S., V.M. and F.J. undertook the timing analyses. E.B. and K.R. designed and built the complex channelized data capture system. K.R. and P. Weltevrede performed the polarization analyses. M.M. carried out the pulse-width analyses using the wavelet transform method. E.B. and W.C. built and designed the beamformer used by MeerTRAP. J.v.d.E. and S.M. performed the Swift analysis. D.A.H.B., J.B. and P.W. obtained and analyzed data from the SALT and SAAO-1m telescopes. D.A.H.B. acknowledges support from the National Research Foundation. F.J. and M.S. undertook analysis of the extant data. S.B. assisted in planning and scheduling the MeerKAT observations. S.S., F.J., M.S., R.F., L.N.D. and M.C.B. contributed to discussions about the nature of the source.

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Abstract

The radio-emitting neutron star population encompasses objects with spin periods ranging from milliseconds to tens of seconds. As they age and spin more slowly, their radio emission is expected to cease. We present the discovery of an ultra-long period radio-emitting neutron star, PSR J0901–4046, with spin properties distinct from the known spin and magnetic-decay powered neutron stars. With a spin-period of 75.88 s, a characteristic age of 5.3 Myr, and a narrow pulse duty-cycle, it is uncertain how radio emission is generated and challenges our current understanding of how these systems evolve. The radio emission has unique spectro-temporal properties such as quasi-periodicity and partial nulling that provide important clues to the emission mechanism. Detecting similar sources is observationally challenging, which implies a larger undetected population. Our discovery establishes the existence of ultra-long period neutron stars, suggesting a possible connection to the evolution of highly magnetized neutron stars, ultra-long period magnetars, and fast radio bursts.

1 Introduction

Radio pulsars are rotation-powered neutron stars, which emit coherent beams of radio emission generated by highly relativistic particles in regions above their magnetic poles. Their known spin periods (P) range from 1.4 ms to 23.5 s and they are divided into various sub-classes (e.g. rotating radio transients, millisecond pulsars, magnetars - <https://www.atnf.csiro.au/research/pulsar/psrcat/>) depending on their observational properties. Particle acceleration and abundant electron–positron pair production is postulated to be an essential condition for the coherent radio emission from pulsars, with the particle acceleration potential expected to be lower for larger spin periods. As seen in most neutron stars, the radio emission is also expected to be strongly inhibited, or cease if the magnetic field configuration and strength, exceed the quantum critical field ($B_{\text{cr}} = 4.413 \times 10^{13}$ G) [1]. Here, we present the discovery of a highly-magnetized 75.88 s period radio-emitting neutron star, PSR J0901–4046 which challenges these conditions for, and the nature of, the radio emission and raises questions about the spin evolution of neutron stars in general.

2 The Data

2.1 The discovery and properties of PSR J0901–4046

PSR J0901–4046 was a serendipitous single pulse discovery at 1284 MHz on 27 September 2020, in an observation directed at the high mass X-ray binary, Vela

X-1, during simultaneous image and time domain searches by the Meer(more) TRAnsients and Pulsars (MeerTRAP - <https://www.meertrap.org/>) and ThunderKAT (<http://www.thunderkat.uct.ac.za>) projects at the MeerKAT radio telescope in South Africa. The pulse was initially detected in the MeerTRAP beamformed data in a single coherent tied-array beam of angular diameter ~ 45 arcseconds. A review of the MeerTRAP data for that observation revealed that there were further wide, but weaker pulses, which were missed by the real-time single pulse detection system. A total of fourteen pulses were identified in the beamformed time domain searches, which were regularly spaced in a span of ~ 30 minutes. A periodicity analysis resulted in an initial period of $P = 75.89 \pm 0.01$ seconds. The corresponding full time and frequency integration image of the field revealed an associated point source at the location of the coherent beam. These data were re-imaged at the smallest possible integration time of 8 seconds and more pulses were identified. An initial inspection of the 8-second images from two other epochs where MeerTRAP data were not available, also revealed that the source exhibited a consistent periodicity. These snapshot images allowed the source to be localized to arcsecond precision. The deepest image of the field shows a partially visible, diffuse shell-like structure surrounding PSR J0901–4046, which is possibly the supernova remnant from the event that formed the neutron star. The complexity of the field in terms of diffuse emission requires additional analysis to determine a robust association of this radio shell with PSR J0901–4046. No known pulsars are located within 2 degrees of this sky location.

A total of six L-band (856 – 1712 MHz) and one UHF-band (544 – 1088 MHz) observations have been performed between September 2020 and May 2021. During these, we detect single pulses from every rotation of the source. The L-band data have resulted in the timing solution shown in Table 1. Despite the large jitter in the pulse shapes of single pulses, we obtain remarkably stable pulse profiles over the various epochs due to the high signal-to-noise ratios (S/Ns). Using 29 times of arrival (ToAs), typically two per epoch, over 7.4 months, we measure timing residuals with a low root-mean-square (rms) of 5.7 ms (see Extended Data Figure 1). When compared to the pulse period, the fractional accuracy of $\sim 7 \times 10^{-5}$ is comparable to the most accurately timed millisecond pulsars. We do not find any evidence of timing noise or covariance of spin parameters with position. PSR J0901–4046 has a best fit dispersion measure (DM) of 52 ± 1 pc cm $^{-3}$ and average half-power pulse widths of ~ 300 ms at both L- and UHF-band suggesting no evidence for radius-to-frequency mapping. We measure pulse-averaged peak flux densities of 89.3 ± 2.7 mJy beam $^{-1}$ and 169.3 ± 14 mJy beam $^{-1}$ at L-band and UHF-band, respectively, with a period-averaged flux density of 408 ± 5 μ Jy beam $^{-1}$ at L-band. The measured DM corresponds to distances of approximately 0.3 and 0.5 kpc according to the γ MW16 [2] and NE2001 [3] Galactic electron density models, respectively. The period ($P = 75.88$ s) and period derivative ($\dot{P} = 2.25 \times 10^{-13}$ s s $^{-1}$; pulsar spin-down rate) correspond to a characteristic age, surface magnetic field strength, and spin-down luminosity of 5.3 Myr, 1.3×10^{14} G and 2.0×10^{28} erg s $^{-1}$ assuming a dipolar magnetic field configuration, respectively (see Figure 1). This discovery confirms the existence of ultra-long period neutron stars.

3 Results

3.1 Radio emission properties

Single pulse analyses of the radio emission from PSR J0901–4046 reveal remarkable and unusual spectro-tempo-polarimetric properties, quite unlike anything seen in known radio pulsars. We notice that the pulse shape is variable both inter-epoch and intra-epoch, but some features persist. Overall, the single pulses studied over 6 epochs can be grouped into 7 different types, namely: normal, quasi-periodic, spiky, double-peaked, partially nulling, split-peak and triple-peaked as shown in Figure 2. Although magnetars are sometimes seen to emit wide, bright radio pulses that comprise several sub-pulse components of varying widths and amplitudes, these are more chaotic within and between subsequent pulses.

In some of the bright pulses we measure a quasi-periodicity in the sub-pulse components which at times appear to be harmonically related between pulses (see Extended Data Figure 2). In some others we see multiple quasi-periods within a single rotation as seen in Extended Data Figure 3. Overall, the quasi-periods are common across the UHF- and L-band observations. We observe the width of the sub-pulse components in PSR J0901–4046 to be exactly half of the quasi-period. The shortest and longest quasi-periods we measure are 9.57 ms (104 Hz) and 338 ms (2.96 Hz) respectively (see Extended Data Figure 4). Similar quasi-periodic features have been observed in fast radio bursts (FRBs) [4]. Radio observations of the magnetar XTE J1810–197 following its 2018 outburst revealed a persistent 50-ms periodicity imprinted on the pulse profile [5]. The most commonly seen quasi-period across all observations is ~ 76 ms (13 Hz), which is $\approx P/1000$. This quasi-period follows the spin-period scaling seen in corresponding values of the micropulses in normal pulsars [6]. This scaling can be most easily associated with the emission of beamlets making up the wider sub-pulses [7], suggesting that the periodicities are caused by a *temporal* or *angular* mechanism rather than the motion of the beamlets in the polar cap region. Alternatively, this quasi-period could be related to sub-pulses or drifting sub-pulses. Each of the sub-pulses or dense, isolated ‘sparks’ (i.e. pair-production sites) are theorized to have a corresponding plasma column, which radiates and generates the observed sub-pulses, which may rotate around the magnetic axis. Such quasi-periodic oscillations are also theorized in models of FRBs, where they are due to magneto-elastic axial (torsional) crustal eigenmodes originating close to the neutron star surface [8]. The eigenfrequencies of these oscillations are expected to depend most strongly on the neutron star mass and the crust equation-of-state [8]. These local crustal oscillations can create Alfvén waves that propagate to larger heights in the magnetosphere, thereby producing an oscillating E in the charge starved region to produce the observed coherent radio emission [9].

Ultimately, it is unclear what causes the quasi-periodicity in PSR J0901–4046. Global magnetoelastic axial (torsional) oscillations are a tempting explanation, but the persistence of our periodicities would require repeated triggers and/or very long damping times. The observed periodicities and frequencies, however, may be consistent with models proposed for magnetars, and the similarity with the periodic feature of the radio-loud magnetar XTE J1810–197 are intriguing. We note that PSR J0901–4046’s position in the $P-\dot{P}$ parameter space is offset from the known magnetar population. We also note that PSR J0901–4046

may differ in other physical quantities (such as in its mass) which we cannot access from our observations but which are likely to play a role in the seismic properties of neutron stars. Hence, differences in the behaviour compared to other neutron stars or magnetars may not be unexpected. It has been proposed [10] that bright coherent radio bursts can be produced by highly magnetized neutron stars that have attained long rotation periods (few 10s to a few 1000s of seconds) called Ultra-Long Period Magnetars (ULPMs). Recently, a source GLEAM-X J162759.5 – 523504.3 with a period of ~ 20 minutes in the radio has been discovered, and is speculated to be a member of this class [11]. X-ray isolated neutron stars (XINS) are nearby cooling neutron stars with spin periods in the range 3.4–11.3 s [12] and are characterized by thermal, soft X-ray, emission. They are believed to be old, strongly magnetized neutron stars despite their non-detection in the radio so far [13]. A few XINS lie above the low-twist death line in Figure 1, implying possible ULPM origins. Interestingly, PSR J0901–4046 also falls in the parameter space (see Figure 1) where these ULPMs are expected to exist. PSR J0901–4046 could potentially be an old magnetar or a member of the ultra-long period magnetars, a result that needs to be confirmed with future multi-wavelength observations. PSR J0901–4046 is therefore an important piece in the puzzle of the evolution of highly magnetized neutron stars and their connection to FRBs.

Typically, when magnetars are radio active, there is also often X-ray emission. We therefore observed PSR J0901–4046 in the X-rays using *Swift*/XRT simultaneously with the MeerKAT observations on 2021-02-01 and 2021-02-02 and did not detect any X-ray emission. Assuming a blackbody spectrum with temperature 1.5 keV, and an equivalent column density of $N_{\text{H}} = 4.32 \times 10^{21} \text{ cm}^{-2}$, we place 3-sigma upper limits of $L_{\text{X1}}(2 - 10 \text{ keV}) < 1.6 \times 10^{30} \text{ erg s}^{-1}$ and $L_{\text{X2}}(2 - 10 \text{ keV}) < 3.2 \times 10^{30} \text{ erg s}^{-1}$ on the X-ray luminosity for distances $d_1 \approx 0.3 \text{ kpc}$ and $d_2 \approx 0.5 \text{ kpc}$, respectively. The location of PSR J0901–4046 in the $P - \dot{P}$ parameter space is consistent with it having spun-down from a magnetar-like period of 10 s in $\sim 5 \text{ Myr}$, assuming a braking index of 3. However, we do not find any evidence for radical changes in the \dot{P} as seen in most magnetars in the 7.4 months since discovery. Additionally, while magnetars are observed to have shallow radio spectra (e.g. [14, 15]), PSR J0901–4046 has a measured L-band in-band spectral index of -1.7 ± 0.9 , which is more consistent with the pulsar population. Canonical, rotation powered pulsars are observed to have X-ray luminosities much smaller than their spin-down luminosities, with on average $L_{\text{X}} \approx 10^{-3}$ [16]. Conversely, magnetars are seen to have $L_{\text{X}} \gtrsim 1$. For PSR J0901–4046, based on the X-ray luminosity upper limit and the spin-down \dot{E} in Table 1, we see $L_{\text{X}} \lesssim 10^2$. This places it closer to magnetars but is not constraining. Additionally, the single pulse brightness is seen to vary significantly in the 8,726 2-second integration time images, across the 6 L-band and 1 UHF-band epochs. The source appears to have secularly grown fainter (see Extended Data Figure 5 and Table 2), from a mean pulse brightness of $16.4 \pm 7.9 \text{ mJy beam}^{-1}$ for the observations centered on 59246.087481292554 to $12.9 \pm 5.2 \text{ mJy beam}^{-1}$ on 59343.62301600376, suggesting a dynamic magnetosphere transforming on timescales much faster than associated with the characteristic age, τ . If this is indeed part of a long-term dimming of the source, and not a short-term variation, then it is also reminiscent of radio-loud magnetars transitioning into quiescence.

The single pulse polarization profiles of PSR J0901–4046 show complex structure, and on average are more circularly than linearly polarized (see Extended Data Figure 6). This

is not unexpected in radio-loud neutron stars, particularly magnetars. The magnetar J1622–4960 exhibits different categories of pulses of varying polarization fractions. One particular category shows a higher value of circular polarization. The Faraday rotation measure (RM) towards PSR J0901–4046 is measured to be $-64 \pm 2 \text{ rad m}^{-2}$. The RM of PSR J0901–4046 is consistent with the contribution from the smoothed Galactic foreground [17] and with the RMs of nearby pulsars. This therefore precludes the presence of a significant intrinsic RM imparted at the source. A phase resolved histogram of the polarization position angle shows the characteristic S-shaped curve expected from a rotating magnetic dipole (see Supplementary Figure 3). This suggests that the line-of-sight passes close to the magnetic pole as we see the S-shaped curve even within a 1% duty cycle. This is consistent with our constraint on the impact parameter of $\beta \lesssim 0.2^\circ$, using a rotating vector model fit.

4 Discussion

The PSR J0901–4046 pulses classified as split-peak are the most common, $\sim 33\%$ of all pulses across all observations, closely followed by a combination of the quasi-periodic and partially nulling pulses which together form $\sim 34\%$. The normal and spiky pulses comprise $\sim 27\%$ and $\sim 6\%$ respectively. A comparison of the energies of the various pulse shape archetypes shows that despite the enormous variability seen in the pulse profile shapes, their energies span more or less the same range (see Supplementary Figure 8). For instance, we lose $\sim 40\%$ of the energy to the dropouts/dips seen in the quasi-periodic and partially nulling pulses, which when accounted for by modelling the pulse envelope, is similar to the energy distribution of the ‘split-peak’ and possibly also the ‘normal’ pulses. This suggests that the pulses with dropouts/dips are not drastically brighter than the other types, implying that an overall increase in particle flow cannot be responsible.

The measured period implies an extremely large pulsar light-cylinder (of radius $R_{LC} = cP/2\pi = 3.62 \times 10^6 \text{ km}$) and consequently a relatively compact polar cap (with radius $R_p = \sqrt{2\pi R^3/cP} = 16.62 \text{ m}$, where $R = 10 \text{ km}$). For an assumed emission height of hundreds of kilometers above the surface, the beam width, and consequently the duty cycle of PSR J0901–4046 is small ($\sim 1\%$) and found to be consistent with the empirical scaling relation between pulse width and spin period ($W \propto P^{-0.5}$) observed in canonical pulsars (e.g. [18]). PSR J0901–4046 is seen to lie in the $P-\dot{P}$ pulsar parameter phase space far from the other recently discovered slowest spinning radio emitting pulsars with periods of 23.5 s [19] and 12.1 s [20] respectively. It is also located beyond the ‘death line’ as defined by the RS75 [21] and CR93 [22] inner vacuum-gap (IVG) curvature radiation models for radio emission (see Figure 1). These models suggest pulsars in this region cannot support the pair-cascade production just above the pulsar polar cap in their inner magnetospheres that is required to sustain the observed radio emission. This is because at large spin periods, it is no longer possible to achieve the increase in thickness of the vacuum gap above the neutron-star polar cap needed to maintain the required potential difference for pair production. This leads to the cessation of radio emission. However, PSR J0901–4046 does lie above the space-charge-limited flow (SCLF) radio emission model death line where pair cascade can be supported through non-relativistic charges flowing freely from the polar cap if there is a multipolar magnetic field configuration. Unambiguous signatures of the presence of

multipolar components close to the neutron star surface have been seen in magnetars [SGR 0418 + 5729; 23], and more recently in an accreting millisecond pulsar [PSR J0030 + 0045; 24, 25] suggesting a likely ubiquity of a multipolar magnetic field configuration in neutron stars.

The putative boundary for radio quiescence in Figure 1 indicated by B_{cr} lies about an order of magnitude below the position of PSR J0901–4046. The quantum process of single photon pair production ($\gamma \rightarrow e^+e^-$) is expected to dominate below the B_{cr} line resulting in predominantly ‘radio loud’ pulsars. The quantum process of photon splitting ($\gamma \rightarrow \gamma\gamma$) is expected to dominate above the B_{cr} line resulting largely in ‘radio quiet’ pulsars due to the suppression of pair creation. PSR J0901–4046 lies above, and at a similar distance from the B_{cr} line as many of the magnetars. Unlike magnetars the radio emission of PSR J0901–4046 has a small duty cycle, but like the magnetars it is highly variable. High-B radio pulsars have on occasion been observed to exhibit magnetar-like activity and have been termed ‘quiescent magnetars’ [26]. Radio emission from magnetars is usually transient and often follows a high-energy outburst (e.g. [27]). It is therefore useful to see how long this source has been a radio emitter and if any previous unidentified high-energy transient has been seen in this region. We did not find any historical high-energy transients coincident with the location of PSR J0901–4046. Unfortunately, none of the relevant radio continuum surveys, TIFR GMRT Sky Survey (TGSS) [28], Sydney University Molonglo Sky Survey (SUMSS) [29] or the Rapid ASKAP Continuum Survey (RACS) [30], were sensitive enough to detect the source given its current time-averaged flux of a couple of hundred micro-Janskys. Analyses of the Parkes Multibeam Pulsar Survey (PMPS) data [31] from nearby pointings also did not detect the source. The nearest pointing should have been sensitive enough, but a combination of radio frequency interference and the hardware high-pass filter likely prevented a detection.

The discovery of a ~ 117 s and 118 s periodicities in the multi-wavelength (including radio) brightness changes of AR Scorpii (AR Sco; a radio pulsating white dwarf binary system) [32] was interpreted as dipole emission from a spinning down of a magnetic white dwarf and not as a neutron star [33, 34]. Given the similarity in period to PSR J0901–4046 we therefore searched for multi-wavelength counterparts in archival data to determine whether it could be a related system. We identified a 17th mag Gaia source, offset by $\sim 1''$ in right ascension and $\sim 3''$ in declination from the radio coordinates, as a possible optical counterpart. Initial follow-up photometry with the South African Astronomical Observatory (SAAO) 1-m telescope showed indications of long term variability in the star. However, spectroscopic observations with the Southern African Large Telescope (SALT) revealed the optical source to be an A-type star, with narrow Balmer absorption lines. As we see no evidence for hydrogen or helium emission lines and no distinct secondary star component in the spectrum, we rule out the possibility of PSR J0901–4046 being an AR Sco type system, or associated with this A-type star. There are no other obvious counterparts brighter than 20–21 mag in this region. While the spin-period of PSR J0901–4046 might be consistent with a white dwarf, we do not see any multi-wavelength support for this.

To ascertain if there is an un-pulsed radio component which might be attributed to a pulsar wind nebula, or perhaps indicate emission of a non-neutron star origin, we imaged follow-up

MeerKAT visibility data that was recorded at a higher time resolution of 2 seconds. After removing the epochs that contain pulsed emission we obtain a 3σ upper limit on the peak brightness of persistent radio emission of $18 \mu\text{Jy beam}^{-1}$ at 1284 MHz (see Extended Data Figure 7). We also find no evidence for pulsed or continuum emission outside of the narrow pulse window, but the radio shell is still present. The extreme ratio of the peak on-pulse flux to the off-pulse flux, the large first period derivative, the timing properties, and the lack of evidence for detections at other wavelengths supports our hypothesis that PSR J0901–4046 is a radio emitting neutron star with one of the longest known periods.

5 Implications for the population of radio-emitting neutron stars

Although modern pulsar surveys are sensitive to a wide range of radio emitting neutron stars, the serendipitous discovery of PSR J0901–4046 has revealed some of the biases that still remain, and highlights that there may be many more sources like this to be found. The long duration of the pulse, low DM and long period are problematic for commonly used single pulse and periodic pulsar search techniques. The very narrow duty cycle suggests a strong bias where many other similar systems may have beams missing the Earth completely. This suggests that there are many more neutron stars in the Galaxy than the known population suggests, unless many pulsars continue to emit for longer than previously thought or if there is an evolutionary link to another class of neutron star such as the magnetars [35], or perhaps a combination of all of these. The position of PSR J0901–4046 in the $P-\dot{P}$ parameter space along with the unusual single pulse properties such as quasi-periodicity and partial-nulling, make it a potentially very useful target for understanding the radio emission properties of neutron stars across the population. Future image and time domain searches for similar long-period objects could prove vital to our understanding of the Galactic neutron star population and potentially links to FRBs.

Methods

Calibration of interferometric imaging data

The MeerKAT observations of the field around PSR J0901–4046 are summarised in Table 2. Nine distinct observations were used, eight of which used MeerKAT’s L-band (856 – 1712 MHz) receivers, and one of which was observed at UHF band (580 – 1015 MHz). Total on-target times (T_{obs}) and correlator integration times per visibility point (T_{int}) are listed in Table 2. The latter is what limits the time resolution of any individual image of the field. The ‘discovery’ observations, associated with observations of Vela X-1 from the ThunderKAT project, were taken with the correlator configured to deliver 32,768 spectral channels. The follow-up (DDT) observations that targeted PSR J0901–4046 directly used 4,096 channels. For the imaging data the observations were in all cases averaged down to 1,024 channels prior to the commencement of the processing.

The approach to imaging the field was common for all observations. Each observation contains 5 minutes scans of the standard primary calibrator source J0408–6465, and the scans of the target field were bracketed by observations of the nearby secondary calibrator J0825–5010, which was observed for 2 minutes for every 15 minutes on the target for the ThunderKAT data, and for every 30 minutes for the DDT observations. The calibrator scans

were flagged in order to remove radio frequency interference, and the low-gain edges of the telescope's bandpass response. Bandpass, delay, and flux-scale corrections were derived from the observations of the primary calibrator, and time-dependent complex gain and delay corrections were derived from the scans of the secondary. These corrections were then applied to the target data. These steps were all performed using the CASA package [36].

Following the application of the referenced calibration, the target data were flagged using the TRICOLOUR (<https://github.com/ska-sa/tricolour/>) software. The target field was imaged using WSCLEAN [37]. Deconvolution was allowed to proceed in an unconstrained fashion. The field exhibits some complex radio morphology, thus a cleaning mask was derived from the first image, after which the imaging was repeated with deconvolution only proceeding within the masked regions. The frequency dependence of the sky was captured by imaging the data in eight separate sub-bands, using a fourth-order polynomial fit to capture spectral curvature, mainly an instrumentally-induced property due to the frequency dependent antenna primary beam response and the broad bandwidth. A sky area ($3.12 \times 3.12 \text{ deg}^2$) much larger than the main lobe of the primary beam ($\sim 1 \text{ deg}$ at FWHM) was imaged in order to deconvolve bright off-axis sources that are detected through the primary beam sidelobes. The use of the cleaning mask, spectral settings, and large sky area in this second imaging run are all to ensure a reliable model for subsequent self-calibration, which consisted of solving for instrumental phase and delay corrections for every 32 seconds of data using the CUBICAL package [38]. The scripts used to perform the data reduction process also provide an exhaustive list of the calibration and imaging parameters, and can be found online (<https://github.com/IanHeywood/oxkat> v0.2) [39].

Snapshot imaging of PSR J0901–4046

To expedite the production of per-integration time images, we first subtract a model of the sky that captures most of the bright emission, but critically does not include any clean components that are associated with PSR J0901–4046 itself. For each MeerKAT observation, the self-calibrated data were imaged, the resulting model images were masked at the position of PSR J0901–4046, and the modified model was inverted into a set of model visibilities, which were then subtracted from the data. Images could then be made for each correlator dump time (8 or 2 seconds) to search for pulsed emission from the target. In the case of the ThunderKAT data the visibilities were first phase-rotated to the position of PSR J0901–4046. Since the dominant emission in the field has been subtracted, small images around the target are viable, and no deconvolution needs to be performed under the (valid) assumption that PSR J0901–4046 is unresolved by MeerKAT. This speeds up the imaging process considerably.

Extended Data Figure 5 shows the peak brightnesses of the pulses as detected in 8,726 2-second snapshot images from the six L-band epochs with this integration time. The pulse brightness varies significantly, however no pulses are missed at the sensitivity limit of our observations, with the exception of the cyan region in the lower left panel, where data were lost due to lightning. The mean RMS noise the snapshot images being $350 \mu\text{Jy beam}^{-1}$ with a standard deviation of $50 \mu\text{Jy beam}^{-1}$. The right hand column of panels in Extended Data Figure 5 shows the pulse brightness expressed as a signal-to-noise (S/N) ratio. The

brightness is measured as the peak pixel value in a 400 pixel box centered at the position of PSR J0901–4046. The noise is taken to be the standard deviation of the pixels in an off-source box of equivalent size. The blue curve on the right hand column of panels shows the S/N ratio of the peak pixel in the off-axis box.

A search for persistent (off-pulse) radio emission

Jointly imaging and deconvolving the visibilities used to produce the 2-second images results in the image shown in the left panel of Extended Data Figure 7. The accumulated pulse emission results in the prominent compact source in the centre of the image, with a peak brightness of $40 (\pm 5.2) \mu\text{Jy beam}^{-1}$. Identifying the timestamps of the pulses shown in Extended Data Figure 5 allows us to re-image the data with those integration times excluded in order to search for off-pulse (persistent) radio emission associated with PSR J0901–4046. This process results in the image shown on the right hand panel of Extended Data Figure 7. There is a $4.3 \mu\text{Jy beam}^{-1}$ ($\sim 1\sigma$, $\sigma = 4.7 \mu\text{Jy beam}^{-1}$) peak in the pulse-subtracted radio map spatially coincident with the peak of the pulsed emission in the image formed from the full dataset. We can thus place a 3σ upper limit on the peak brightness of a persistent radio source coincident with the peak of the pulsed emission of $18 \mu\text{Jy beam}^{-1}$. The other sources visible in Extended Data Figure 7 are faint compact sources that were not deconvolved in the per-epoch imaging process, and thus not subtracted from the visibilities.

In the deepest image we have made in Extended Data Figure 7, there is diffuse emission in the region of PSR J0901–4046. More analysis is needed to see if it is somehow associated with PSR J0901–4046 as this is a complex region of the sky with lots of diffuse emission. However if it were attributable to radio emission from a supernova remnant that could be associated with PSR J0901–4046 it would suggest that the source was much younger than the characteristic age and have important implications for its evolution. None of the features visible in Extended Data Figure 7 are above the noise floor of the 2 second images, and thus do not contaminate the measurements presented in Extended Data Figure 5.

DM estimate

The DM of each single pulse was estimated by maximizing for structure within the burst envelope using `DM_phase` (https://github.com/danielemichilli/DM_phase). The structure-optimized DM is determined by maximizing the coherent power across the bandwidth [40]. We de-dispersed the data over a trial DM range of $49.0 \leq \text{DM} \leq 54.0 \text{ pc cm}^{-3}$ in steps of 0.1 pc cm^{-3} . The uncertainty on each DM estimate was calculated by converting the standard deviation of the coherent power spectrum into a standard deviation in DM via the Taylor series. We measure a weighted average DM of $52 \pm 1 \text{ pc cm}^{-3}$ for PSR J0901–4046.

Timing

The MeerTRAP pipeline searches data in real time and for each transient event detected, it writes out a short SIGPROC filterbank file that contains a few seconds of the original input data stream centered around the detection time of the associated event. For each detection, a substantially smaller, second-stage candidate file is also created as follows: the native resolution filterbank file is dedispersed at the detection DM reported by the search pipeline, a reduced time span of the data window equal to the dispersion delay of the candidate

DM is extracted and lastly the time and frequency resolution of the data are reduced to an appropriate level according to the reported pulse width for the event (larger widths correspond to a larger acceptable degradation factor of the data). Second-stage candidate files are small enough to be stored *en masse*, but the native resolution filterbank files are not; only those deemed very likely to contain a genuine astrophysical event by an automated classifier are kept, the rest are otherwise regularly deleted. For the original detection of PSR J0901–4046, we thus had access to a filterbank file with our native resolution of approximately $306.24 \mu\text{s}$ and 1024 channels across the 856 MHz bandwidth at L-band. A detailed visual inspection of second-stage candidate plots around the time of discovery showed that we had actually made more detections of the source, but the unusual nature of the wide pulses and the relatively low DM meant that they were not initially labelled as astrophysical and the associated filterbank data had already been deleted. However, there is still sufficient information in the second-stage candidate files to allow the manual determination of an arrival time, albeit with significantly increased uncertainty; we thus obtained a total of 14 approximate arrival times from the day of the discovery.

The uncertainties on those times of arrival (ToAs) were estimated as part of the initial periodicity analysis, which consisted of a simple Bayesian linear regression with three parameters: a pulse period, an initial phase term, and an uncertainty scaling factor where the underlying assumption was that the uncertainty on each arrival time was proportional to the pulse width reported by the search pipeline. This yielded the initial period estimate of $P = 75.89 \pm 0.01$ seconds previously mentioned, and a root mean square uncertainty of 100 ms on the arrival times. These 14 initial ToAs were then used along with the imaging data to further constrain the pulse period. They are also included in the timing analysis (see the orange points in Extended Data Figure 1).

We generated ToAs for each of the two 30 minutes observations on each of the 6 MeerKAT L-band observing epochs between February and May 2021. The filterbank data recorded with the TUSE instrument were used for timing. These data also had a resolution of approximately $306.24 \mu\text{s}$ and 1024 channels across the 856 MHz bandwidth at L-band. The data were folded on to 65536 phase bins and incoherently dedispersed using the `DSPSR` software package [41]. Further manipulation of the data used the tools available in the `PSRCHIVE` package [42]. Radio-frequency interference was removed manually using `PSRZAP`.

To maintain a coherent timing solution, we secured available observing slots at the Parkes radio telescope in Australia and monitored PSR J0901–4046 over 4 epochs. The observations were performed using the Ultra-Wideband receiver (UWL) across a 704–4032 MHz band. The data were coherently de-dispersed at the DM given in Table 1, divided into 1024 phase bins for each of 3328 frequency channels of 1 MHz bandwidth, and written to disk. The duration of the observations varied between 1 and 2 hours. The RFI environment at Parkes is such that many frequency channels in the data contained strong baseline fluctuations on a time scale comparable to the typical pulse duration of PSR J0901–4046, which required applying additional layers of RFI mitigation to make the averaged pulse unambiguously identifiable in each integrated observation. An updated version of the `clfd` (<https://github.com/v-moreello/clfd>) RFI cleaning package described in [43] was used to that effect. The relatively steep spectrum of the source meant that it was not easily

detectable above 1.8 GHz even after cleaning and so we only used frequencies in the range 0.704 to 1.8 GHz for generating arrival times.

The initial folding and timing analysis for both telescopes used the best known period and DM at the time and the position determined from the imaging. For the MeerKAT data a noise-free template was made by fitting von Mises functions to the data from the first epoch in February 2021 using the `PSRCHIVE` program `PAAS`. A similar procedure was followed for the Parkes UWL data also using the first observation from February 2021. For both the MeerKAT and Parkes data ToAs were obtained by using `PSRCHIVE`'s `PAT` which cross-correlated the template with an average profile for each of the 30 minute observations. A ToA (the first red diamond in Extended Data Figure 1) was also determined from the single pulse obtained from the filterbank file saved from the discovery observation by cross-correlating it with the MeerKAT template (As the filterbank file was significantly shorter in duration than the period of the source we padded it with random Gaussian noise so that it could be folded using `DSPSR` and preserve the timing information).

Timing was done using `TEMPO2` [44] with the JPL DE436 planetary ephemeris (<https://naif.jpl.nasa.gov/pub/naif/JUNO/kernels/spk/de435s.bsp.lbl>). The ToAs were fit using a model including the period P and period derivative \dot{P} and a jump between the UWL data and the MeerKAT data (Another, fixed jump of 6.115060037383178 s, was needed for a few of the arrival times from the discovery epoch due to an uncertainty of one data buffer that occurred in these early data). We do not fit for position as it is well determined from the imaging as described in previous sections. An astrometric precision of about $\sim 1''$ results in a change in arrival time over a year of less than 2.3 ms, so is not affecting the measured parameters, especially the \dot{P} which can show a covariance when there is less than a year of data. We also do not fit for DM as this is sufficiently well determined from optimizing the S/N of the individual pulses and a jump is fit between the UWL and MeerKAT data.

Once a coherent timing solution was obtained across the entire data set the filterbanks were refolded and dedispersed and a new noise-free template was made, based on the sum of all of the detected pulses, and new ToAs were obtained and a new final timing solution was determined and is presented in Table 1 with the residuals shown in Extended Data Figure 1. Each 30-minute observation is the average of about 24 pulses and so there is some pulse phase jitter, which can be seen in the MeerKAT data, where the error bars are smaller than the data points and also less than the scatter in the arrival times. However the overall timing RMS is only 5 ms which is just under 1/10000th of the pulse period which is approaching that of the best millisecond pulsars and is attributable to the very high signal to noise but also suggests that the arrival times are not significantly affected by the pronounced variations in the pulse properties and likely reflects the overall similarity of the pulse envelope.

Quasi-periodicity Analysis

Radio loud neutron stars are seen to exhibit a rich variety of intensity variations over timescales of microseconds to years. Within an individual pulse, sub-structures manifest most conspicuously as sub-pulses/components that have random-like but also, pulse- and source-dependent continuous or quasi-periodic variability in time intervals.

Quasi-periodicities are usually seen as repeating “micropulses” [45] forming part of “microstructure” superimposed on the wider sub-pulses (e.g. [46]). Microstructure is usually theorized to be caused by mechanisms related to magnetospheric radio emission. There is often a variety of timescales observed, even within a given source (e.g. [47]), for pulsars with typical periods of about ~ 1 s, sub-pulses tend to have widths of a few to tens of ms. Timescales and periodicities in the shorter micropulses tend to scale like $P_\mu \sim P/1000$ [6, 7], where often the micropulse duration and periodicity scale like $w_\mu \sim P_\mu/2$ [6].

We followed standard methods [6, 47] to determine the timescales of the short-time structure for PSR J0901–4046. An auto-correlation function (ACF) of pulses detected by the TUSE pipeline containing both sub-pulses and microstructure, will show a peak at zero-lag corresponding to the DC component, followed by a peak at short timescales due to possible microstructure and then a second peak associated with the sub-pulse structure [48]. We extracted the timescale of the sub-pulses by performing an ACF analysis of the single pulse intensities. We compute the cross-correlation of the de-dispersed signal as a function of time with a delayed copy of itself given by,

$$\text{ACF}(\tau) = \int_0^t f(t)f(t-\tau) dt, \quad (1)$$

where τ is the time lag. The zero-lag value, associated with self-noise, was excised from the ACF. Given the complexity of the structures seen in the single pulses, we visually inspected each pulse to understand what can and cannot be inferred about the timescales. The characteristic separation or quasi-period of the sub-pulses (defined as P_2) measured across the whole observing band is given by the time lag of the peak of the first feature following the zero-lag in each ACF. We only measure the the quasi-periods for those pulses which are visually obvious in the ACFs.

As a result, we observe some of the quasi-period values to be harmonically related as shown in Extended Data Figures 2 and 4, and in some cases, the separations between the peaks is almost the separation between the dips or dropouts in power. Occasionally, two or more quasi-periods co-exist in a single rotation. Upon visual inspection we notice that some pulses in PSR J0901–4046 exhibit variations in widths as well as quasi-periods within a single rotation as seen in Extended Data Figure 3. We do not observe these quasi-periodic pulses to follow a trend in time, nor do they appear to precede or follow any other particular type of pulse.

These quasi-periodic features could be interpreted as sub-pulses or drifting sub-pulses. Although the latter are usually characterized by a fixed, from pulse to pulse, separation between sub-pulses. The sparking discharge from IVG models explains sub-pulses through non-stationary spark-associated plasma flows. The IVG is discharged in the form of dense isolated sparks (i.e. pair-production sites), where the lateral size and distance between the sparks are comparable to the gap height [21]. Each spark has a corresponding coherent plasma column, which radiates and generates the observed sub-pulse components in pulsars. According to this ‘Spark’ model [49], up to three sparks can be accommodated in the polar

cap of PSR J0901–4046, which is much fewer than the number of features typically seen in its single pulses.

The dominant quasi-period of ~ 76 ms (corresponding to a frequency of 13 Hz) follows the spin-period scaling seen in corresponding values of the micropulses in normal pulsars [6] (see Extended Data Figure 4). This scaling can be most easily associated with the emission of beamlets making up the wider sub-pulses [7], implying that the periodicities are caused by a *temporal* or *angular* mechanism rather than a *radial* mechanism. Apart from the consistent scaling in the value of the quasi-period, the appearance of several periodicities within one sub-pulse has also been seen in normal pulsars (e.g. [6, 45, 47]). Overall, this makes it tempting to associate these structures to “normal” microstructure in pulsars in a similar manner.

However, the appearance of the dropouts (see e.g. the top-left example in Extended Data Figure 2) is different to that of normal micropulses. In contrast, it is very reminiscent of quasi-periodic oscillation (QPO) features seen both in the emission of hard short X-ray bursts and the tail of energetic giant flares of magnetars. The “dropout” pattern seen in the quasi-periodic and partially nulling pulses is very unusual for pulsar radio emission. Nevertheless, we establish that these dropouts are a genuine feature of the emission of the source. We see these features at all epochs in the filterbank data recorded by both the TUSE and APSUE instruments, as well as the raw voltage data extracted directly from the F-engine. These features track the dispersion of the source and, importantly, are not seen in the “off pulse” emission. Additionally, we do not observe these features in any of the test pulsar (J0820–4114) observations at the start of each epoch, thereby ruling out the possibility of instrumental artifacts. The magnetar QPOs with frequencies between 18 to 1800 Hz are often interpreted as a result of seismic vibrations of the neutron star (see e.g. [26, 50] and references therein). Global magnetoelastic axial (torsional) oscillations are expected to be able to explain the frequencies as low as seen here. They have also been put forward as explanations for sequences of emission features seen in Fast Radio Bursts (FRBs) invoking magnetar oscillations [8]. Adopting such an explanation for the quasi-periodicities observed in PSR J0901–4046 would demand, given their persistence in our observations, a repeating triggering mechanism or modes with long-lived eigenfrequencies. The nature of the modes, their eigenmodes and, importantly, their damping times depend strongly on the physics and properties of the neutron star’s crust, the mass, the equation-of-state and, to some degree, also on magnetic field strength [26]. Most references discuss damping time lengths only for the duration of the seen QPOs or FRB emission sequences, i.e. tens of ms to seconds (e.g. [8]), which is clearly too short to explain the consistency of our observed periodicities over many weeks and months (see Extended Data Figure 4).

Interestingly, radio observations of the magnetar XTE J1810-197 during its renewed radio brightness following its 2018 outburst also revealed a persistent 50-ms periodicity in its pulse profile seen for about 10 days. As reported by Levin et al. (2019) [5], this emission feature was imprinted on the pulse profile simultaneously at a range of observed radio frequencies between 1 and 9 GHz. The frequency of this feature of about 20 Hz is obviously similar to that of our dropouts in PSR J0901–4046. In XTE J1810–197 the feature showed a remarkable constancy in phase relative to the main pulse profile, implying that the

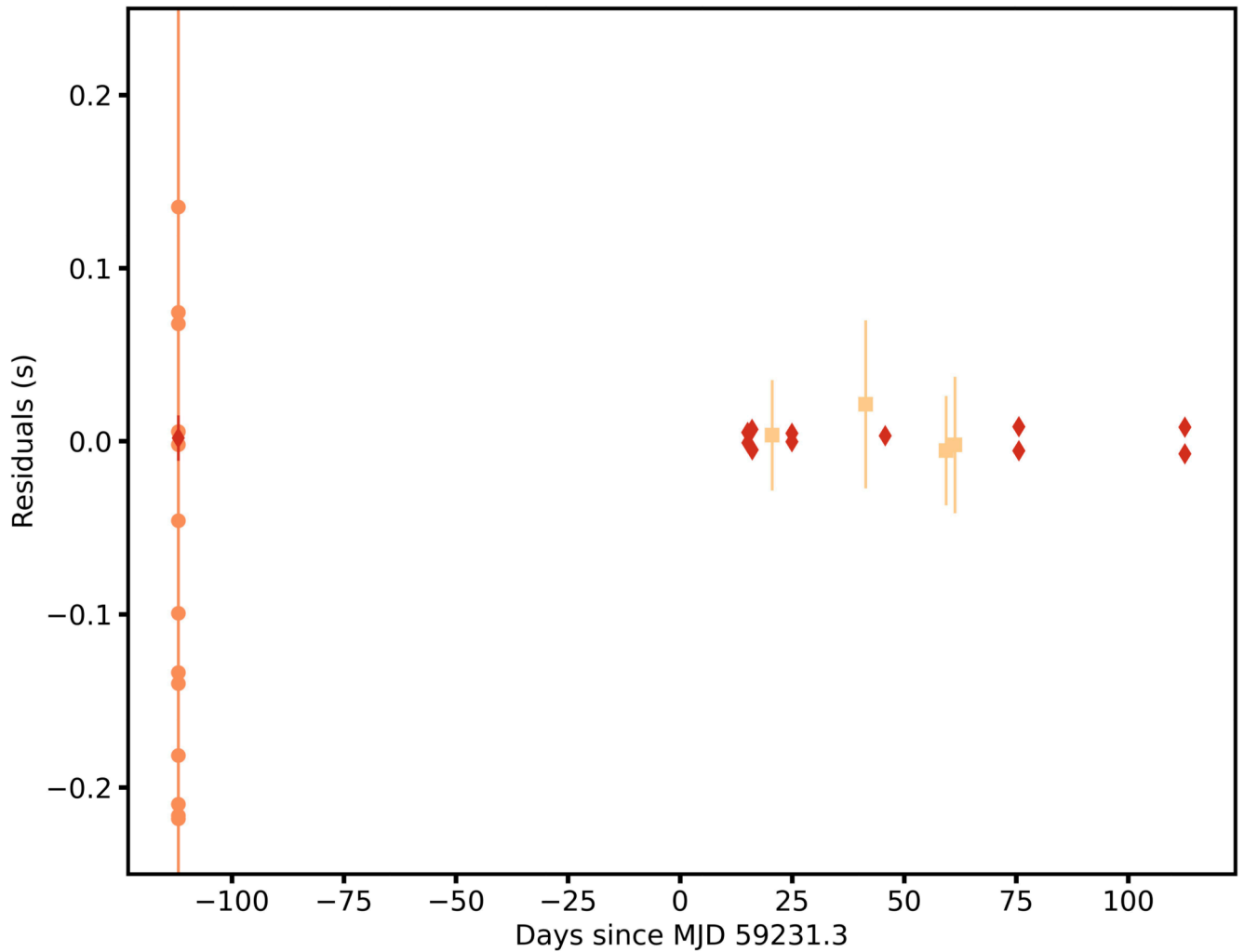
periodicity is not a temporal modulation of the emitting source, but must be due to a periodic structure in the radiation beam pattern that sweeps across the Earth as the pulsar rotates. Levin et al. suggested that this pattern could arise from a *stable* structure on the surface of the neutron star at the base of the magnetic field lines hosting the emitting particles for the radio component. The stability of the pattern would require a frozen-in wave pattern of radial dimension of the surface height, temperature or magnetic field. Such a pattern would be reminiscent of surface waves in the neutron star crust, similar to those discussed above, but they would need to be stable over at least 10 days.

X-ray Follow-up

We requested Neil Gehrels *Swift* Observatory (*Swift*) observations to search for a candidate X-ray counterpart to PSR J0901–4046. We obtained three observations for a total exposure of 7419.030 s (ObsIDs 00014019002, 00014019003, 00014019004, taken on MJD 59245.83, 59352.04, and 59353.29 with individual exposures of 3872.021 s, 1345.595 s, and 2703.971 s, respectively). The three observations were separated by 1, 9, and 10 days from their closest radio observation, respectively. We extracted an image using the XRT product generator online reduction pipeline (https://www.swift.ac.uk/user_objects/index.php) [51]. A visual inspection of the image showed that the source was not detected, therefore we use the SOSTA tool within the XIMAGE environment to perform source statistics. SOSTA allows one to use a local background to determine the significance of a source and its count rate, rather than a global background estimate. Extracting events at the nominal position of PSR J0901–4046 from a square box with 16 pixels side ($\approx 38''$) we obtained a 3-sigma upper limit to the count rate of $R^{up} \approx 1.57 \times 10^{-3}$ cts/s in the 0.5–10 keV energy range. We then assumed a blackbody spectrum with temperature 1.5 keV, and an equivalent column density of $N_H = 4.32 \times 10^{21}$ cm $^{-2}$ (i.e. the Galactic equivalent column density in the direction of PSR J0901–4046). Using WebPPIMS (<https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl>, PIMMS v4.11b.) we estimated a 3-sigma upper limit to the 0.5–10 keV X-ray flux of $F < 1.2 \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$, which at a distance of $d_1 \approx 328$ pc and $d_2 \approx 467$ pc corresponds to a 3-sigma upper limit to the X-ray luminosity $L_{X1} < 1.6 \times 10^{30}$ erg s $^{-1}$ and $L_{X2} < 3.2 \times 10^{30}$ erg s $^{-1}$, respectively.

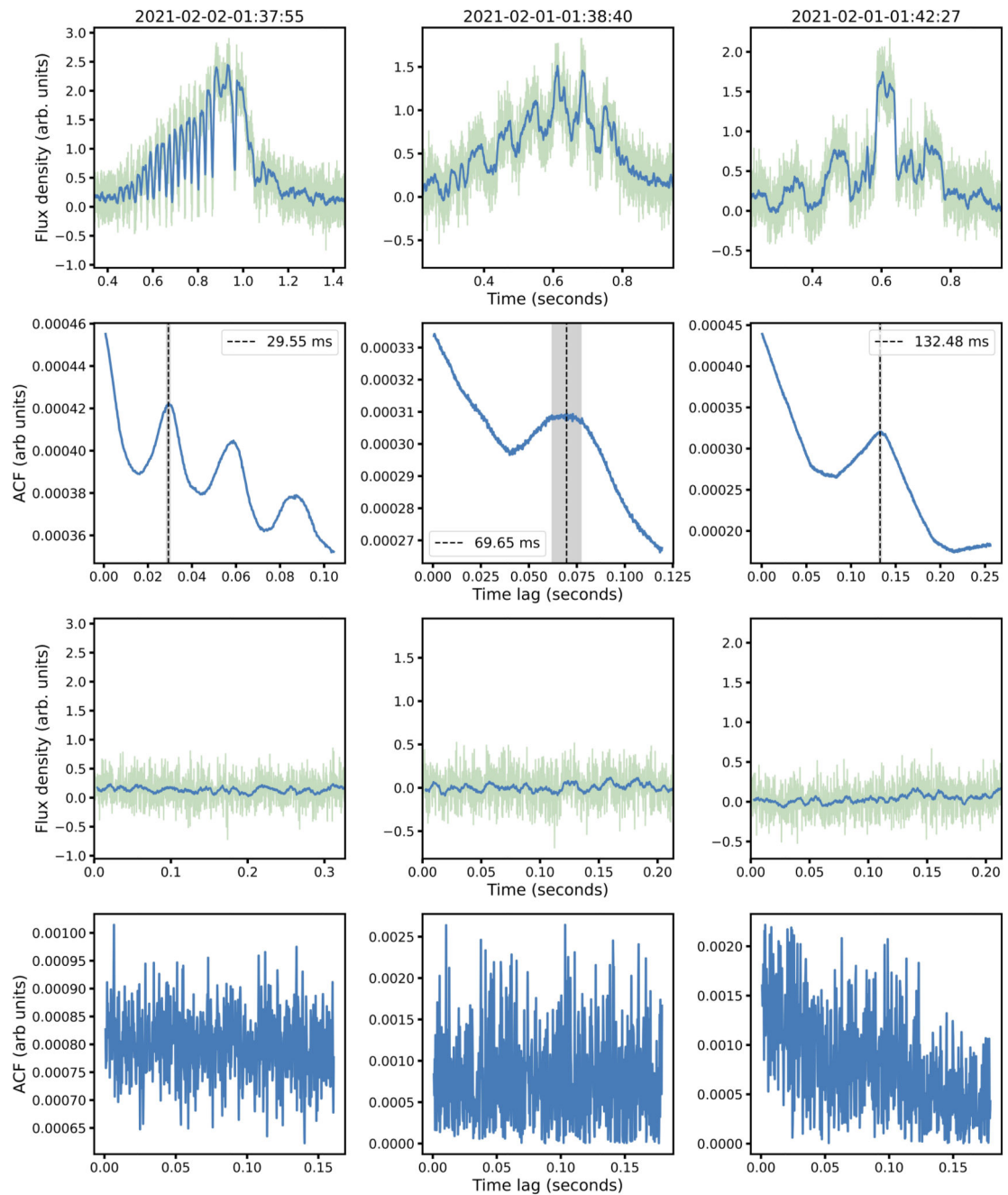
We note that the XMM-Newton archive includes two archival observations of the Vela X-1 field (ObsID 0406430201 and 0841890201, taken in 2018 and 2019, respectively). In such pointings PSR J0901–4046 is located at the very edge of the EPIC-MOS image, and in one of the two observations only one of the MOS cameras was active (the other was switched off for telemetry reasons). Given that the response of the instrument is not ideal so close to the edge of the CCD, and calibration might not be reliable, we decided to not use these observations, and rely solely on the more conservative - but likely more robust - upper limit derived from the *Swift* data.

Extended Data



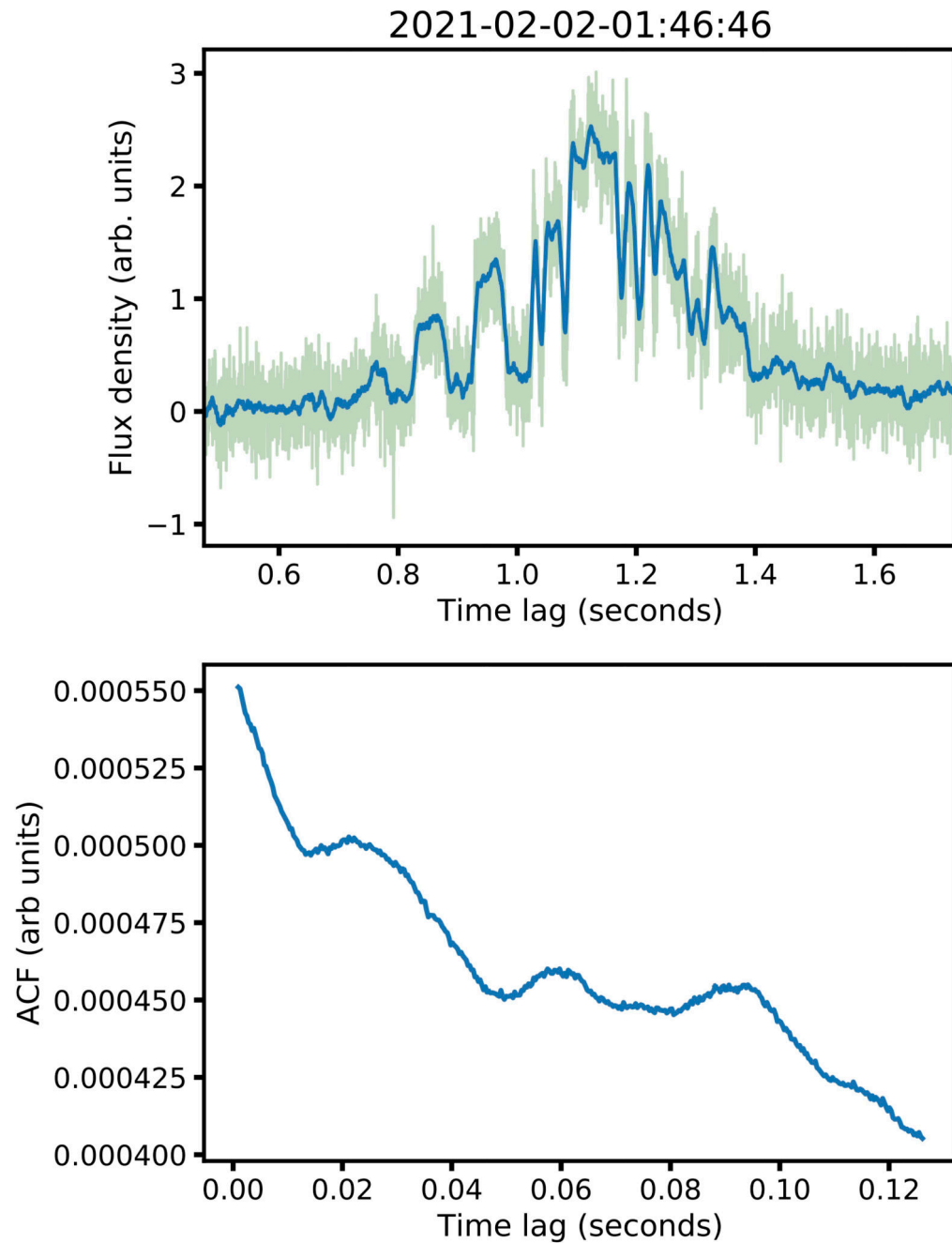
Extended Data Figure 1.

Timing residuals of PSR J0901–4046. The residuals from the best fit timing model given in Table 1. The orange data points are determined from the original MeerTRAP detection images, the first red diamond corresponds to a single pulse and the remaining red diamonds are determined from each of the half hour long follow-up observations with MeerKAT. The error bars are $1-\sigma$. We used the L-band MeerKAT data for the timing analysis. The light coloured data points are from the Parkes UWL observations.

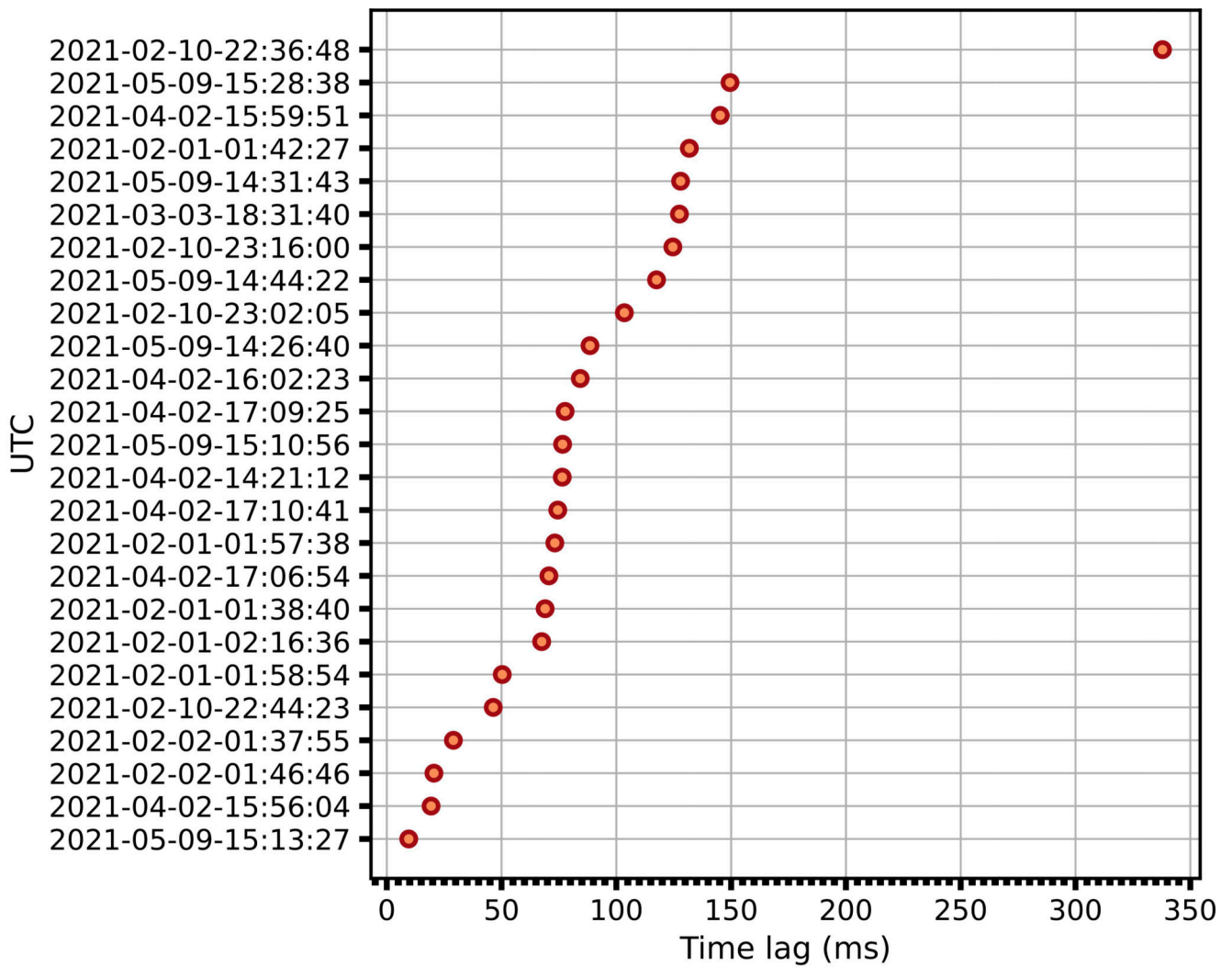


Extended Data Figure 2.

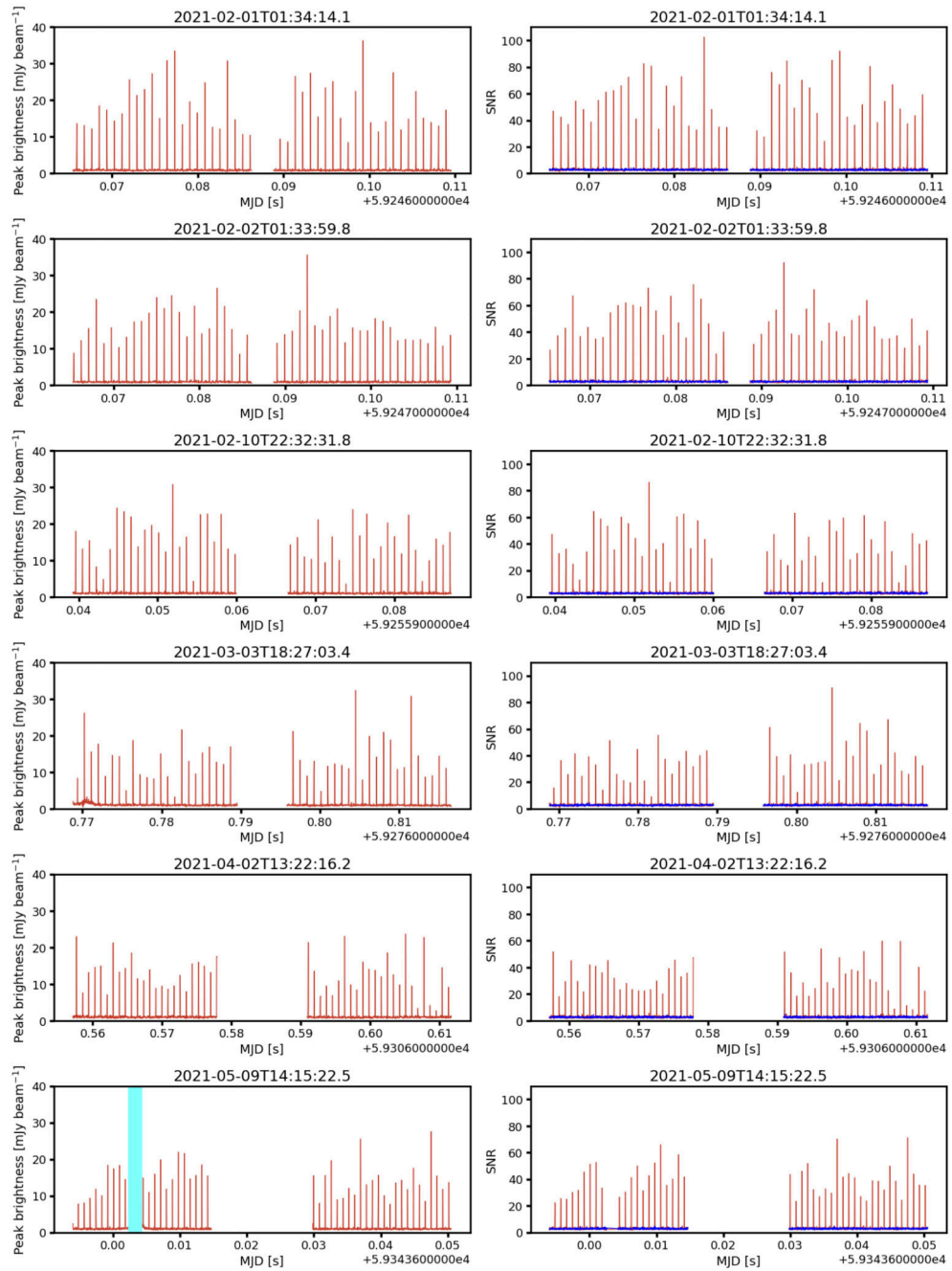
Examples of quasi-periodic pulses. The top two rows show pulse profiles and their corresponding ACFs at $306.24\mu\text{s}$ resolution, respectively. The value the of quasi-period is indicated by the black vertical lines. The bottom two rows show the off-pulse regions and their corresponding ACFs.

**Extended Data Figure 3.**

Example of a pulse exhibiting more than one quasi-period. Some quasi-periodic pulses as shown here, exhibit multiple quasi-periods within a single rotation.

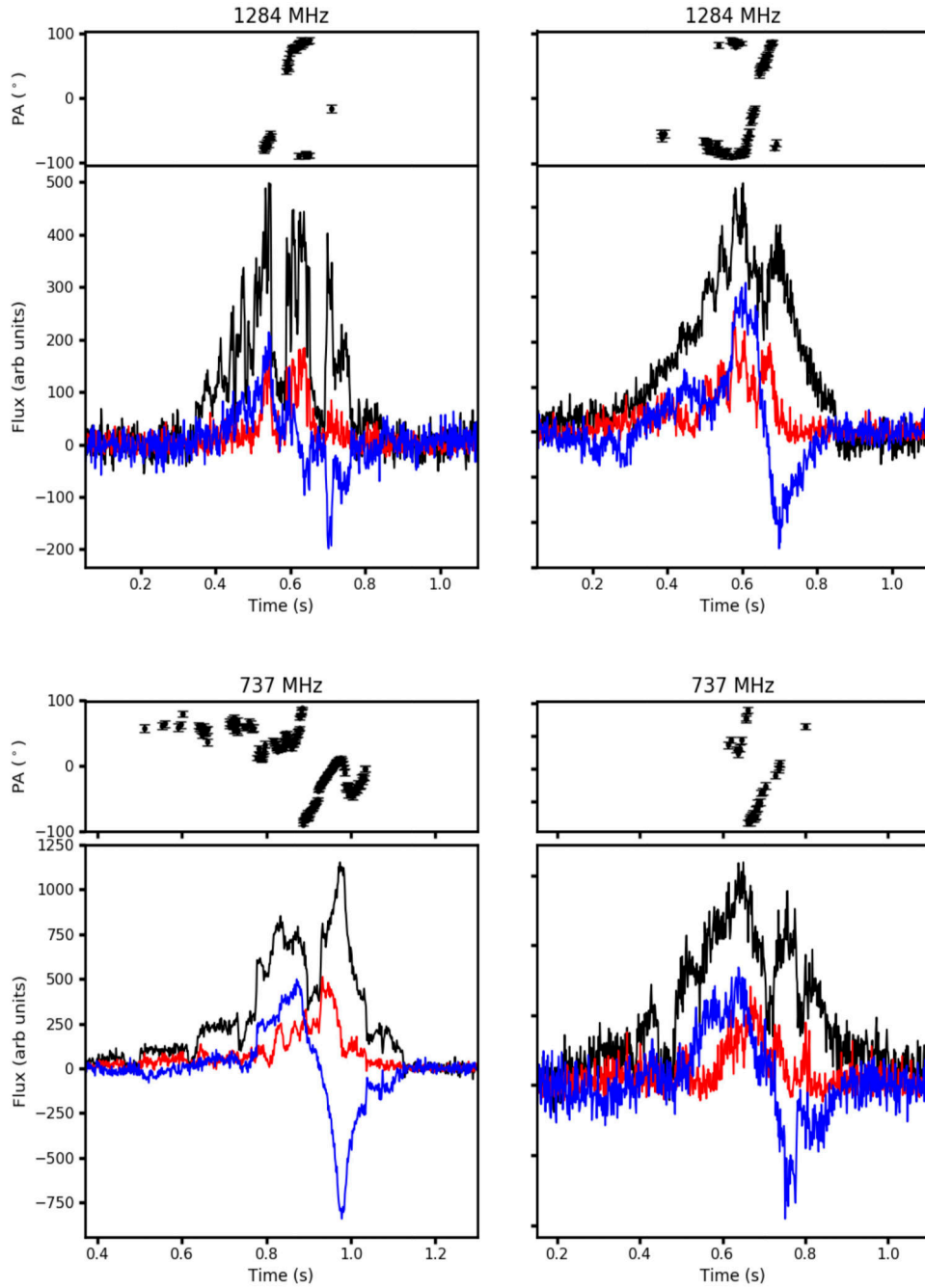
**Extended Data Figure 4.**

Estimates of the quasi-period across all epochs. The (orange) circles are the measured quasi-periods for each single pulse. The most commonly observed average quasi-period is 75.82 ms with the minimum period being 9.57 ms. The lags are arranged in lag length and not in time order.



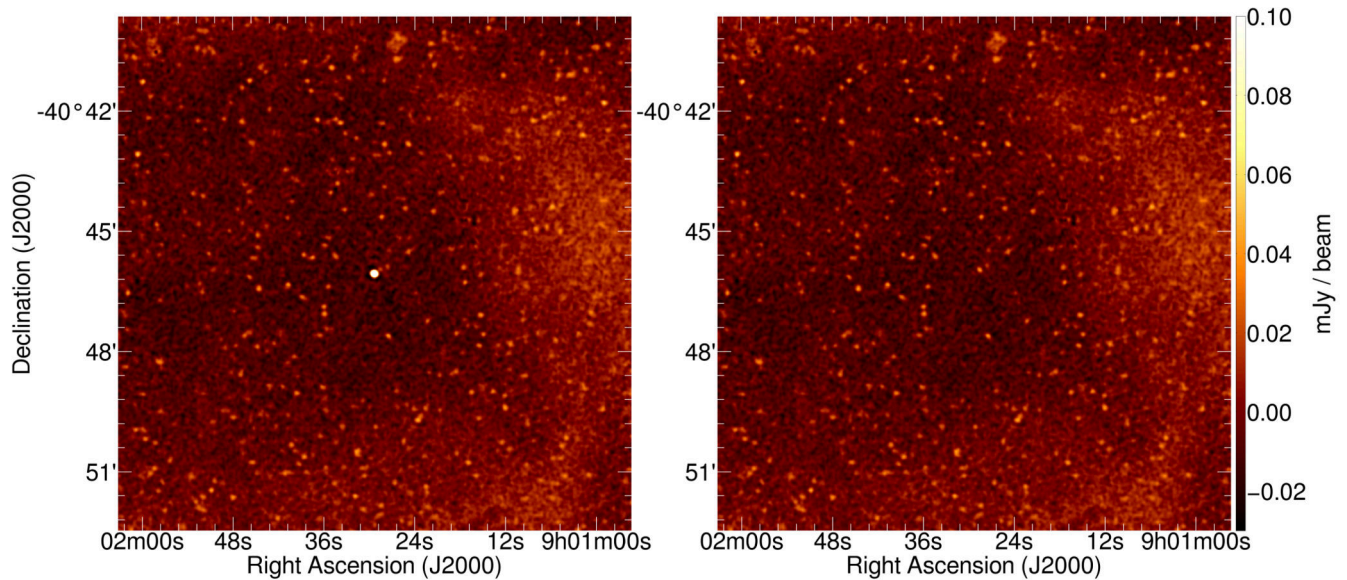
Extended Data Figure 5.

Radio light-curves of PSR J0901–4046. A regular series of pulsed emission detected in the L-band snapshot imaging for six observing epochs. Please refer to Section 5 for details.



Extended Data Figure 6.

Polarization profiles of PSR J0901–4046 at 1.3 GHz and 700 MHz. Top Panel: Time series of two single pulses of PSR J0901–4046 at 1284 MHz. Bottom Panel: Two different single pulse time series at 737 MHz. For both panels, the total intensity is represented by the black solid line, the red solid line denotes the linear polarization while the blue solid line denotes circular polarization. The polarization position angle is not absolutely calibrated at 737 MHz.



Extended Data Figure 7.

MeerKAT image of the PSR J0901–4046 region at 1.28 GHz. The left hand panel shows the image with the pulsed emission included, and the right hand panel shows the same field following the removal of the integration times containing pulses. No persistent radio source is associated with PSR J0901–4046 to a 3σ limit of $18 \mu\text{Jy beam}^{-1}$. The diffuse shell-like structure that surrounds PSR J0901–4046 is partially visible, possibly the supernova remnant from the event that formed the neutron star.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

The data that support the findings of this study are available at <https://github.com/manishacaleb/MKT-J0901-4046>.

Code availability

All code necessary for analyses of the data are available on GitHub and Zenodo: <https://github.com/IanHeywood/oxkat>, <https://doi.org/10.5281/zenodo.1212487>

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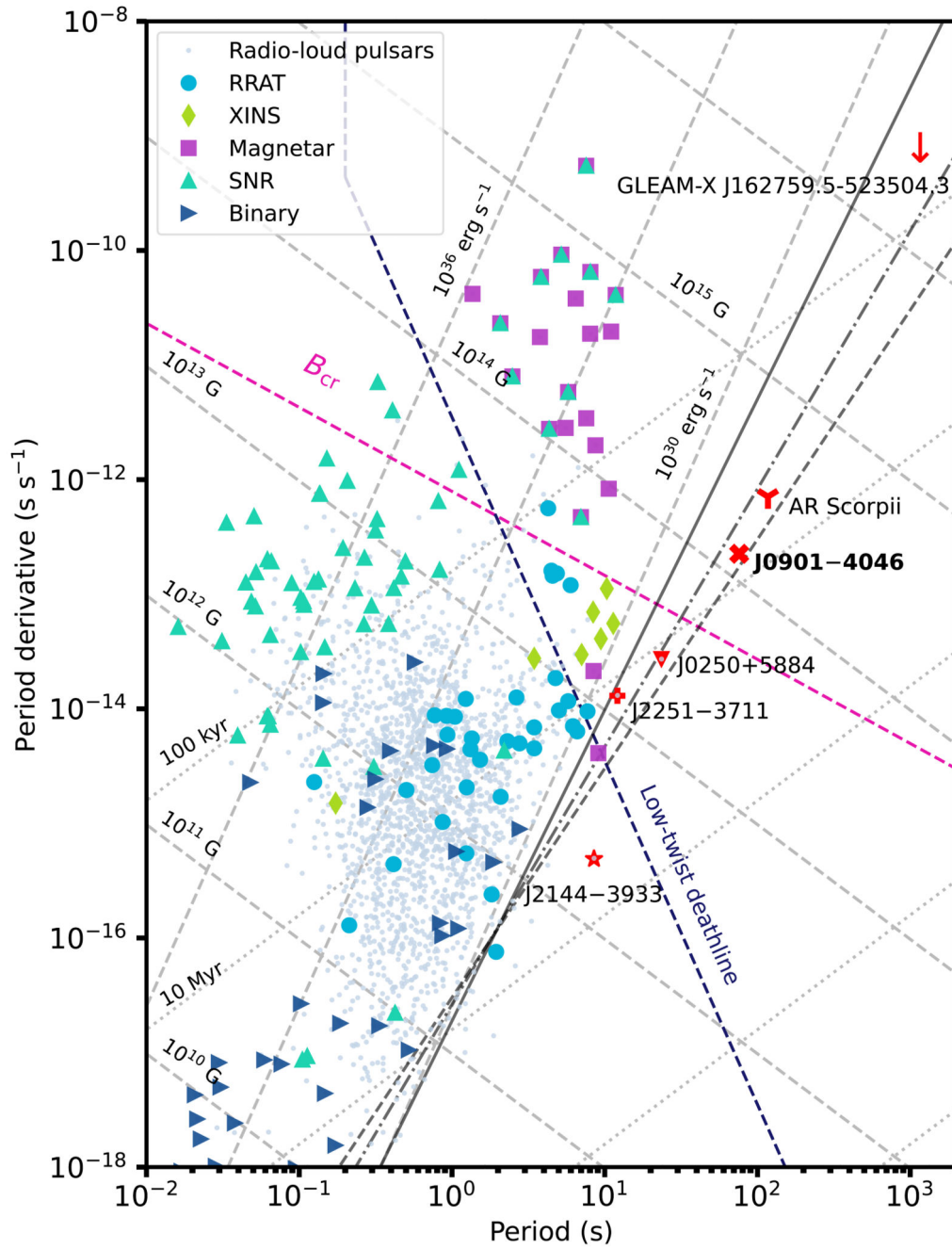


Fig. 1.

$P-\dot{P}$ diagram based on the ATNF pulsar catalog. The various sub-classes of pulsars are represented by the markers in the legend. The longest spin period radio pulsars and the white dwarf binary system AR Sco are highlighted in red. Lines of constant age and magnetic field are shown as dotted and dashed lines respectively. The lower right corner of the figure represents the ‘death valley’ with various death lines from the literature, where sources below these lines are not expected to emit in the radio. The solid death line represents Equation 9 in CR93 [22]. In dot-dashed and dashed are the death lines modeled

on curvature radiation from the vacuum gap and SCLF models as shown by Equations 4 and 9 respectively in [52]. Sources above the low-twist death line are potential ultra-long period magnetars.

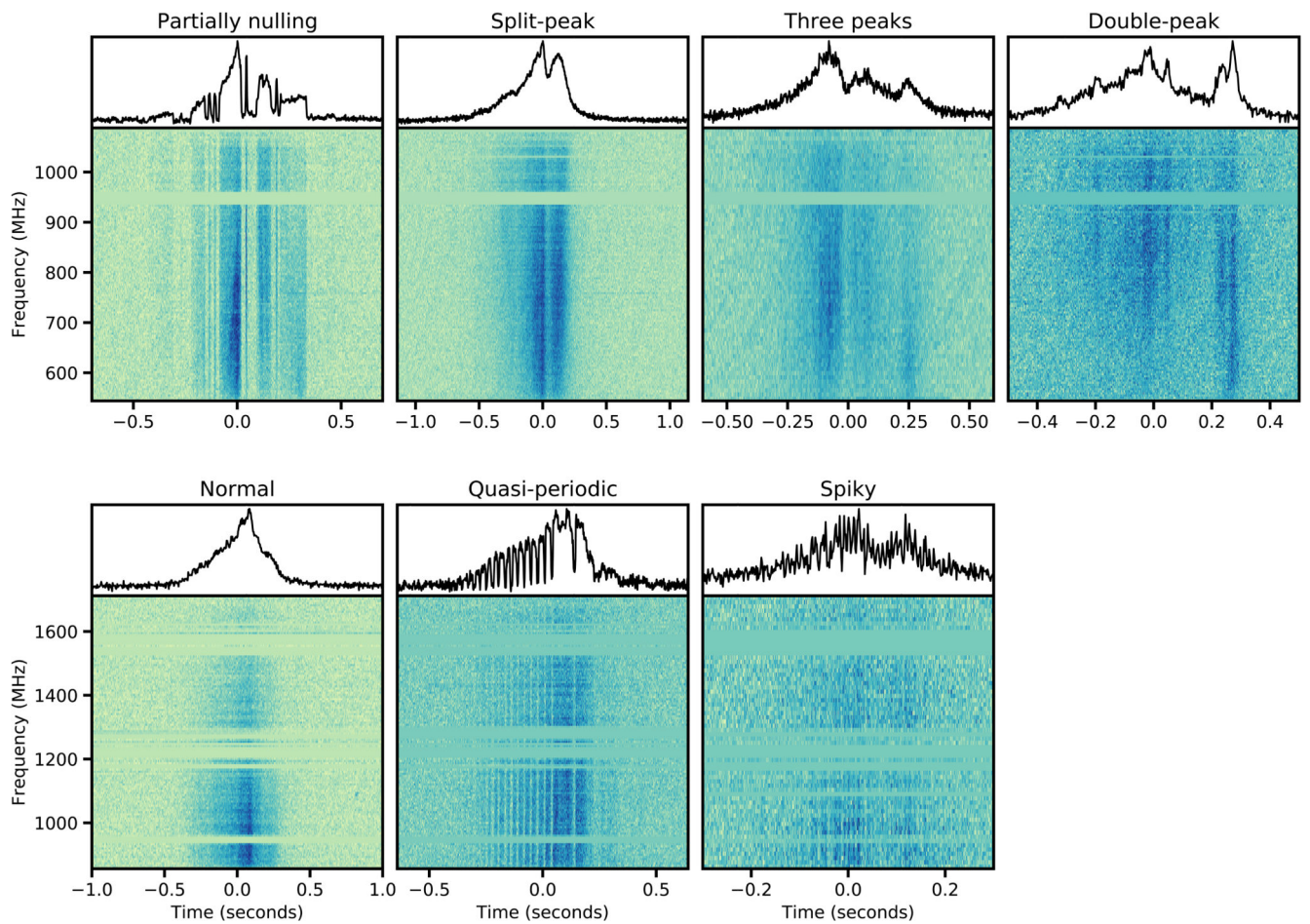


Fig. 2.

Gallery of the pulse morphology types of PSR J0901–4046. The morphological type is given in the title for each panel. The top panels are pulses observed in the UHF-band while the bottom panels are pulses observed at L-Band.

Table 1

Pulsar timing and model parameters for PSR J0901—4046. This includes the measured quantities and the derived quantities from the timing analysis over the span of this observing campaign. Uncertainties in parentheses as $1-\sigma$ errors on the last significant quoted digit.

Data and model fit quality	
Modified Julian Date (MJD) range	59119.0 to 59343.6 (7.4 months)
Number of TOAs	29
Weighted root mean square timing residual (ms)	5.7
Measured quantities	
Right ascension, α (J2000)	$09^{\text{h}}01^{\text{m}}29.249^{\text{s}} \pm 1.0''$
Declination, δ (J2000)	$-40^{\circ}46'02.984'' \pm 1.0''$
Pulse frequency, ν	$0.013177739873 \pm 9.9 \times 10^{-12} \text{ s}^{-1}$
First derivative of pulse frequency, $\dot{\nu}$	$-3.9 \pm 0.2 \text{ s}^{-2}$
Pulse period, P	$75.88554711 \pm (6 \times 10^{-8}) \text{ s}$
Period derivative, \dot{P}	$(2.25 \pm 0.1) \times 10^{-13} \text{ s s}^{-1}$
Dispersion measure, DM	$52 \pm 1 \text{ pc cm}^{-3}$
Full width at half maximum, W_{50} (L-band)	$299 \pm 1 \text{ ms}$
Full width at half maximum, W_{50} (UHF-band)	$296 \pm 4 \text{ ms}$
Spectral index, α	-1.7 ± 0.9
Rotation measure, (RM)	$-64 \pm 2 \text{ rad m}^{-2}$
Fractional linear polarization	$12.2 \pm 0.2 \%$
Fractional circular polarization	$21.0 \pm 1.9 \%$
Inferred quantities	
Distance (YMW16), d_1	328 pc
Distance (NE2001), d_2	467 pc
Characteristic age, τ	5.3 Myr
Surface dipole magnetic field strength, B	$1.3 \times 10^{14} \text{ G}$
Spin-down luminosity,	$2.0 \times 10^{28} \text{ erg s}^{-1}$
Period-averaged radio luminosity, L_{1400} at d_2 . .	$89 \mu\text{Jy kpc}^2$
X-ray Luminosity, $L_X(0.5 - 10\text{keV})$ at d_2	$\lesssim 3.2 \times 10^{30} \text{ erg s}^{-1}$

Table 2

MeerKAT observations of the PSR J0901–4046 field. The first three rows labelled TKAT are discovery observations targeting the Vela X-1 field, while the rest labelled DDT are follow-up observations. See the text for details.

Date UT, J2000	Block ID	RA J2000	Dec J2000	Band	N_{ant}	T_{obs} h	T_{int} s	Origin
2020-09-25	1600995961	09 ^h 02 ^m 06.86 ^s	−40°33′16.9″	L	59	0.5	8	TKAT
2020-09-27	1601168939	09 ^h 02 ^m 06.86 ^s	−40°33′16.9″	L	61	0.5	8	TKAT
2020-10-11	1602387062	09 ^h 02 ^m 06.86 ^s	−40°33′16.9″	L	60	0.5	8	TKAT
2021-02-01	1612141271	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	L	64	1	2	DDT
2021-02-02	1612227667	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	L	61	1	2	DDT
2021-02-10	1612994791	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	L	62	1	2	DDT
2021-03-03	1614794470	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	L	63	1	2	DDT
2021-04-02	1617367872	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	L	63	1	2	DDT
2021-04-02	1617376889	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	UHF	62	1	2	DDT
2021-05-09	1620567645	09 ^h 01 ^m 29.35 ^s	−40°46′03.6″	L	62	1	2	DDT