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

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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 its 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.

Radio pulsars are rotation-powered neutron stars that 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 (for example, rotating radio transients, millisecond pulsars and 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 ($B_c = 4.413 \times 10^{13} \text{G}$)1. Here we present the discovery of a highly magnetized, 75.88 s period, radio-emitting neutron star, PSR J0901-4046, that challenges these conditions for and the nature of the radio emission and raises questions about the spin evolution of neutron stars in general.

The discovery and properties of PSR J0901-4046

PSR J0901-4046 was a serendipitous single-pulse discovery at 1,284 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 that were missed by the real-time single-pulse detection system. A total of 14 pulses were identified in the beamformed time domain searches, which were regularly spaced over a span of ~30 minutes. A periodicity analysis resulted in an initial period of $P = 75.89 \pm 0.01$ s, where the uncertainty is the 1σ error. 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 2 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...
Results

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 six months show quasi-periodic, spiky, double-peaked, partially nulling, split-peak and triple-peaked, as shown in Fig. 2. Although magnetars are sometimes seen to emit wide, bright radio pulses that comprise flux densities of $89.3 \pm 2.7 \text{ mJy beam}^{-1}$ and $169.3 \pm 14 \text{ mJy beam}^{-1}$ at the L band and UHF band, respectively, with a period-averaged flux density of $408 \pm 5 \text{ mJy beam}^{-1}$ at the L band. The measured DM corresponds to distances of approximately 0.3 and 0.5 kpc according to the YMW16 (ref. 21) and NE2001 (ref. 22) Galactic electron density models, respectively. The period ($P = 75.88$ s) and period derivative ($\dot{P} = 2.25 \times 10^{-13} \text{s}^{-1}$) correspond to a characteristic age, surface magnetic field strength and spin-down luminosity of 5.3 Myr, $1.3 \times 10^{14} \text{ G}$ and $2.0 \times 10^{28} \text{ erg s}^{-1}$, respectively, assuming a dipolar magnetic field configuration (Fig. 1). This discovery confirms the existence of ultra-long-period neutron stars.
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 (Extended Data Fig. 2). In some others we see multiple quasi-periods within a single rotation, as seen in Extended Data Fig. 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 (Extended Data Fig. 4). Similar quasi-periodic features have been observed in fast radio bursts (FRBs). Radio observations of the magnetar XTE J1810-197 following its 2018 outburst revealed a persistent 50-ms periodicity imprinted on the pulse profile. The most commonly seen quasi-period across all observations is ~76 ms (13 Hz), which is about equal to $P/1,000$. This quasi-period follows the spin-period scaling seen in corresponding values of the micropulses in normal pulsars. This scaling can be most easily associated with the emission of beamlets making up the wider sub-pulses, 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’ (that is, pair-production sites) are theorized to have a corresponding plasma column, which radiates and generates the observed sub-pulses, which may then 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. The eigenfrequencies of these oscillations are expected to depend most strongly on the neutron star mass and the crust equation of state.

These local crustal oscillations can create Alfvén waves that propagate to larger heights in the magnetosphere, thereby producing an oscillating parallel electric field $E_p$ in the charge-starved region to produce the observed coherent radio emission.

Ultimately, it is unclear what causes the quasi-periodicity in PSR J0901-4046. Global magneto-elastic 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 is 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) that we cannot access from our observations but that are likely to play a role in the seismic properties of neutron stars. Hence, differences in the behaviour compared with other neutron stars or magnetars may not be unexpected. It has been proposed that bright coherent radio bursts can be produced by highly magnetized neutron stars that have attained long rotation periods (few 10s to a few 1,000s 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. X-ray-isolated neutron stars are nearby cooling neutron stars with spin periods in the range $3.4$–$11.3$ s (ref. 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. A few X-ray-isolated neutron stars lie above the low-twist death line in Fig. 1, implying possible ULPM origins. Interestingly, PSR J0901-4046 also falls in the parameter space (Fig. 1) where these ULPMs are expected to exist. PSR J0901-4046 could potentially be an old neutron star.
magnetar or a member of the ULPMs, 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 emit radio waves, there is also X-ray emission. We therefore observed PSR J0901-4046 in the X-rays using Swift’s X-Ray Telescope (Swift/XRT) simultaneously with the MeerKAT observations on 1 February 2021 and 2 February 2021 and did not detect any X-ray emission. Assuming a blackbody spectrum with a temperature of 1.5 keV and an equivalent column density of $N_{\text{H}} = 4.32 \times 10^{20} \text{ cm}^{-2}$, we place 95% upper limits of $L_{\text{X}} (2–10 \text{ keV}) < 1.6 \times 10^{28} \text{ erg s}^{-1}$ and $L_{\text{X}} (2–10 \text{ keV}) < 3.2 \times 10^{29} \text{ ergs}^{-1}$ on the X-ray luminosity for distances $d \approx 0.3 \text{ kpc}$ and $d \approx 0.5 \text{ kpc}$, respectively.

The location of PSR J0901-4046 in the $P$–$P$ parameter space is consistent with it having spun down from a magnetar-like period of 10 s in ~5 Myr, assuming a braking index of 3. However, we do not find any evidence for radical changes in the characteristic age, $\tau_\star$. If this is indeed part of a long-term dimming of PSR J0901-4046, then it is also reminiscent of the pair-cascade production just above the pulsar polar cap in the Ruderman and Sutherland\(^{21}\) and Chen and Ruderman\(^{22}\) inner magnetospheres that is required to sustain the observed variability seen in the pulse profile shapes their energies span more or less the same range (Supplementary Fig. 8). For instance, we lose ~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 pulsars 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 $R_{\text{lc}} = cP/2\pi = 3.62 \times 10^6 \text{ km}$) and consequently a relatively compact polar cap (with radius $R_\theta = \sqrt{2\pi R^2/cP} = 16.62 \text{ m}$, where $R = 10 \text{ km}$). For an assumed emission height of hundreds of kilometres above the surface, the beam width and consequently the duty cycle of PSR J0901-4046 is small (~1%), and is found to be consistent with the empirical scaling relation between pulse width and duty cycle of PSR J0901-4046 as seen in most magnetars (for example, refs. 14,15). PSR J0901-4046 has a measured L-band in-band spectral index of $-1.7 \pm 0.9$, 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 $L_X \approx 10^{-3} \text{ E}$ (ref. 16). Conversely, magnetars are seen to have $L_X \lesssim E$. For PSR J0901-4046, based on the X-ray luminosity upper limit and the spin-down $E$ in Table 1, we see $L_X \lesssim 10^{-2} E$. This places it closer to magnetars but is not constraining. Additionally, the single-pulse brightness is seen to vary substantially in the 8,726 2-second integration time images across the 6 L-band and 1 UHF-band epochs. The source appears to have grown secularly fainter (Extended Data Fig. 5 and Table 2), from a mean pulse brightness of 16.4 \pm 7.9 mJy beam$^{-1}$ for the observations centred on 59246.087481292554 to 12.9 \pm 5.2 mJy beam$^{-1}$ on 59343.62301600376, suggesting a dynamic magnetosphere transforming on timescales much faster than those associated with the characteristic age, $\tau$. 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 (Extended Data Fig. 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 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\(^{21}\) and with the RMs of nearby pulsars. This therefore precludes the presence of a substantial 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 (Supplementary Fig. 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 $\beta \approx 0.2\%$, using a rotating vector model fit.

**Discussion**

The PSR J0901-4046 pulses classified as split-peak are the most common (~33% of all pulses across all observations), closely followed by a combination of the quasi-periodic and partially nulling pulses, which together form ~34%. The normal and spiky pulses comprise ~27% and ~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 (Supplementary Fig. 8). For instance, we lose ~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.

**Table 2** MeerKAT observations of the PSR J0901-4046 field

| Date (UT, J2000) | Block ID | RA (J2000) | Dec (J2000) | Band | $N_{\text{ant}}$ | $T_{\text{int}}$ (h) | $T_{\text{int}}$ (s) | Origin |
|-----------------|----------|------------|-------------|-------|-----------------|----------------|----------------|--------|
| 25 September 2020 | 1600995961 | 09 h 02 min 06.86 s | $-40^{\circ}33^{\prime}16.9^{\prime\prime}$ | L | 59 | 0.5 | 8 | TKAT |
| 27 September 2020 | 1601168939 | 09 h 02 min 06.86 s | $-40^{\circ}33^{\prime}16.9^{\prime\prime}$ | L | 61 | 0.5 | 8 | TKAT |
| 11 October 2020 | 1602387062 | 09 h 02 min 06.86 s | $-40^{\circ}33^{\prime}16.9^{\prime\prime}$ | L | 60 | 0.5 | 8 | TKAT |
| 1 February 2021 | 1612141271 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | L | 64 | 1 | 2 | DD1 |
| 2 February 2021 | 1612227667 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | L | 61 | 1 | 2 | DD1 |
| 10 February 2021 | 1612994791 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | L | 62 | 1 | 2 | DD1 |
| 3 March 2021 | 1614794470 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | L | 63 | 1 | 2 | DD1 |
| 2 April 2021 | 1617367872 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | L | 63 | 1 | 2 | DD1 |
| 2 April 2021 | 1617368889 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | UHF | 62 | 1 | 2 | DD1 |
| 6 May 2021 | 1620567645 | 09 h 01 min 29.35 s | $-40^{\circ}46^{\prime}03.6^{\prime\prime}$ | L | 62 | 1 | 2 | DD1 |

The first three rows labelled TKAT are discovery observations targeting the Vela X-1 field, while the rest labelled DD1 are follow-up observations. $N_{\text{ant}}$, $T_{\text{int}}$ and $T_{\text{int}}$ represent the number of antennas, the total time spent on target, and the correlator integration time per visibility point.
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 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) and more recently in an accreting millisecond pulsar (PSR J0030+0405), suggesting a likely ubiquity of a multipolar magnetic field configuration in neutron stars.

The putative boundary for radio quiescence in Fig. 1 indicated by $B_\text{c}$ 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 $B_\text{c}$ line, resulting in predominantly ‘radio-quiet’ pulsars. The quantum process of photon splitting ($\gamma \rightarrow \gamma\gamma$) is expected to dominate above the $B_\text{c}$ 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 $B_\text{c}$ line to 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’. Radio emission from magnetars is usually transient, and often follows a high-energy outburst (for example, ref. 3). It is therefore useful to see how long this source has been a radio emitter, and if any previously 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 (Tata Institute of Fundamental Research Giant Metrewave Radio Telescope Sky Survey, Sydney University Molonglo Sky Survey or the Rapid Australian Square Kilometre Array Pathfinder Continuum Survey) were sensitive enough to detect the source, given its current time-averaged flux of a couple of hundred $\mu$Jy. Analyses of the Parkes Multibeam Pulsar Survey data 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 probably prevented a detection.

The discovery of $\sim$117 s and $\sim$118 s periodicities in the multi-wavelength (including radio) brightness changes of AR Scorpii (AR Sco; a radio pulsating white dwarf binary system) was interpreted as dipole emission from a spinning down of a magnetic white dwarf and not as a neutron star. 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 17 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 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 unpulsed radio component that 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 were recorded at a higher time resolution of 2 seconds. After removing the epochs containing pulsed emission we obtain a 3σ upper limit on the peak brightness of persistent radio emission of 18 $\mu$Jy beam$^{-1}$ at 1,284 MHz (Extended Data Fig. 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 support our hypothesis that PSR J0901-4046 is a radio-emitting neutron star with one of the longest known periods.

**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, there is an evolutionary link to another class of neutron star such as the magnetars, or perhaps a combination of all of these. The position of PSR J0901-4046 in the $P$–$P$ 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 potential links to FRBs.

**Methods**

**Calibration of interferometric imaging data**. The MeerKAT observations of the field around PSR J0901-4046 are summarized in Table 2. Of the 9 distinct observations used, 8 used MeerKAT’s L-band (856–1,712 MHz) receivers and 1 was observed at the UHF band (580–1,015 MHz). Total on-target times ($T_\text{obs}$) and correlator integration times per visibility point ($T_\text{int}$) 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 before beginning the processing.

The approach to imaging the field was common for all observations. Each observation contains 5-minute 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 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.

Following the application of the referenced calibration, the target data were flagged using the TRICOLOUR software. 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°×3.12 deg) much larger than the main lobe of the primary beam (~1 degree at full-width at half-maximum) was imaged 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 package38. 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. This 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 visible and no deconvolution needs to be performed under the (valid) assumption that the PSR J0901-4046 is unresolved by MeerKAT. This speeds up the imaging process considerably.

Extended Data Fig. 5 shows the peak brightnesses of the pulses as detected in 8,726 2-second snapshot images from the 6 L-band epochs with this integration time. The pulse brightness varies substantially, however no pulses are missed at the sensitivity limits of our observations for February. The cyan region indicates the higher signal-to-noise (S/N) ratio of the peak pixel in a 400-pixel box centred 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 Fig. 7. The accumulated pulse emission results in the prominent compact source in the centre of the image, with a peak brightness of $40.4 \pm 5.2 \mu$Jy beam$^{-1}$. Identifying the timestamps of the pulses shown in Extended Data Fig. 5 allows us to re-image the data with those integration times excluded 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 Fig. 7. There is a 4.3 $\mu$Jy beam$^{-1}$ ($\sim 1\sigma$; $\sigma = 4.7 \mu$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 3$\sigma$ upper limit on the peak brightness of a persistent radio source coincident with the peak of the pulsed emission in the image formed from the full dataset. 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.

**DM estimate.** The DM of each single pulse was estimated by maximizing for structure within the burst envelope using DM, phaseweight (https://github.com/danielrobbendencies/DMphaseweight). The structure-optimized DM is determined by maximizing the coherent power across the bandwidth39. We dedispersed the data over a trial DM range of 49.0 $\pm$ 5.0 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 52.4 $\pm$ 0.1 pc cm$^{-3}$ for PSR J0901-4046.

**Timing.** The MeerTRAP pipeline searches data in real time, and for each transient event it writes out a short SIGPROC filterbank file that contains a few seconds of the original input data stream centred 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 for further processing. 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.

Once a coherent timing solution was obtained across the entire dataset, the filterbanks were refolded and dedispersed, 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 residual shots in Extended Data Fig. 1. Each 30-minute observation is the average of about 24 pulses 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 r.m.s. is only 5 ms, which is just under 1/10,000th of the pulse period, approaches that of the best millisecond pulsars and is attributable to the very high S/N ratio, but also suggests that the arrival times are not greatly affected by the pronounced variations in the pulse properties and probably reflects the overall similarity of the pulse envelope.

**Quasi-periodicity analysis.** Radio-long neutron stars are seen to exhibit a rich variety of intensity variations over timescales of microseconds to years. Within an individual pulse, substructures 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 a series of sub-structure resembling properties of a `microstructure' superimposed on the wider sub-pulses (for example, ref. 6). 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 (for example, ref. 6); for pulsars with typical periods of 1 s, sub-pulses tend to have widths of a few to tens of ms. Timescales and periodicities in the shorter micropulses \( P_\mu \) tend to scale like \( P_\mu \propto P_{1,000} \) (refs. 6, 7), where often the micropulse duration \( (w_\mu) \) and periodicity scale like \( w_\mu \propto P_{1,000} \) (ref. 2).

We followed standard methods\(^6,9\) to determine the timescales of the short-time structure for PSR J0901-4046. An auto-correlation function (ACF) of pulses detected in an overlap region containing the sub-pulses and micropulses will show a peak at zero lag corresponding to the constant (component, followed by a peak at short timescales due to possible microstructure and then a second peak associated with the sub-pulse structure\(^6\). 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 dispersed signal as a function of time \( t \) with a delayed copy of itself, given by:

\[
ACF(\tau) = \int_0^\infty f(t) f(t-\tau) \, dt
\]

where \( t \) 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 pulse, 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 \( (\tau_1, \tau_2, \ldots) \) measured across the whole observed band is given by the timescale of the peak of the first feature following the zero lag in each ACF. We only measure the quasi-periods for those pulses that 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 Figs. 2 and 4) and, in some cases, the separations between the peaks are 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 Fig. 3. We do not observe these quasi-periodic pulses to follow a trend in time, nor do they appear to precede or follow any 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 inside the magnetosphere is often thought to be a major source of these sub-pulses. In addition, the appearance of several periodicities within one sub-pulse has also been seen in normal pulsars (for example, refs. 6, 7). Overall, this makes it tempting to associate these structures to ‘normal’ microstructure in pulsars in a similar manner. However, the appearance of the dropouts (for example, the top-left example in Extended Data Fig. 2) is different from that of normal micropulses. In contrast, it is very reminiscent of quasi-periodic oscillations seen in both the emission of hard 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 generic feature in the ‘microstructure’ of the source. We see these features at all epochs in the filterbank data recorded by both the TUSE and Accelerated Pulsar Search User Supply Equipment (APSUSE) 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 pulses (J0820–4114) observations at the start of each epoch, thereby ruling out the possibility of instrumental artifacts. The magnetar quasi-periodic oscillations with frequencies between 18 and 1,800 Hz are often interpreted as a result of seismic vibrations of the neutron star (for example, refs. 6, 38 and references therein). Global magneto-elastic axial (toroidal) oscillations are expected to be able to explain the frequencies as low as 30 Hz. They have also been forward as explanations for emission features seen in 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\(^9,10\). Most references discuss damping-time lengths only for the duration of the seen quasi-periodic oscillations or FRB emission sequences, that is, tens of ms to seconds (for example, ref. 4), which is clearly too short to explain the consistency of our observed periodicities over many weeks and months (Extended Data Fig. 1).

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.,\(^9\) this emission feature was imprinted on the pulse profile simultaneously at a range of frequencies from 8 to 19 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, and 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 3 observations for a total exposure of 7419.030 s (observation IDs 00014019002, 00014019003 and 00014019004, taken on JD 59245.83, 59352.04 and 59353.29 with individual exposures of 3,872.021 s, 1,345.595 s and 2,703.971 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). A visual inspection of the image showed that the source was not detected; therefore, we used the SOSTA tool within the XIMAGE environment to extract source statistics. SOSTA allows one to use local backgrounds 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 per side (−38°), we obtained a 3σ upper limit to the count rate of \( R_0 = 1.57 \pm 1 \times 10^{-3} \) counts per second in the 0.5–10 keV energy range. We then assumed a blackbody spectrum with a temperature of 1.5 keV and an equivalent column density of \( N_H = 4.3 \pm 1 \times 10^{22} \) cm\(^{-2}\) (that is, 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), we estimated a 3σ upper limit to the 0.5–10 keV X-ray flux of \( F = 1.2 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), which at a distance of \( \approx 328 \) pc and \( d = 467 \) pc corresponds to a 3σ upper limit to the X-ray luminosity of \( L_X = 1.6 \times 10^{32} \) erg s\(^{-1}\) and \( L_{\gamma} = 3.2 \times 10^{32} \) erg s\(^{-1}\).

We note that the XMM-Newton archive includes two archival observations of the Vela X-1 field (observation IDs 0406430201 and 0841890201, taken in 2018 and 2019, respectively). In such pointings, PSR J0901-4046 is located at the very edge of the European Photon Imaging Camera-Metal Oxide Semi-conductor (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 not to use these observations and to rely solely on the more conservative, but probably more robust, upper limit derived from the Swift data.

**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 (https://github.com/IanHeywood/oxkat) and Zenodo (https://doi.org/10.5281/zenodo.1212487).

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Articles Nature Astronomy

31. Manchester, R. N. et al. The Parkes multi-beam pulsar survey—I. observing
28. Intema, H. T., Jagannathan, P., Mooley, K. P. & Frail, D. A. The GMRT
20. Morello, V. et al. The survey for pulsars and extragalactic radio bursts—IV.
18. Johnston, S. & Karastergiou, A. The period–width relationship for radio
19. Tan, C. M. et al. LOFAR discovery of a 23.5 s radio pulsar.
17. Oppermann, N. et al. Estimating extragalactic Faraday rotation.
16. Becker, W. & Trümper, J. The X-ray luminosity of rotation-powered neutron
15. Dai, S. et al. Wideband polarized radio emission from the newly revived
12. Yoneyama, T., Hayashida, K., Nakajima, H. & Matsumoto, H. Universal
9. Lu, W., Kumar, P. & Zhang, B. A unified picture of Galactic and
cosmological fast radio bursts. Mon. Not. R. Astron. Soc. 498, 1397–1405
Beniamini, P., Wadiasingh, Z. & Metzger, B. D. Periodicity in recurrent fast radio bursts and the origin of ultralow period magnetars. Mon. Not. R. Astron. Soc. 496, 3390–3401 (2020).
Harley-Walker, N. et al. A radio transient with unusually slow periodic
11. Woudt acknowledge research support from the National Research Foundation. Annu. Rev. Astron. Astrophys.
37. Offringa, A. R. et al. WSCLEAN: an implementation of a fast, generic wide-field imager for radio astronomy. Mon. Not. R. Astron. Soc. 444, 609–619 (2014).
Kenyon, J. S., Smirnov, O. M., Grobler, T. L. & Perkins, S. J. CUBICAL—fast radio interferometric calibration suite exploiting complex optimization. Mon. Not. R. Astron. Soc. 478, 2399–2415 (2018).
Heywood, I. oxkat: semi-automated imaging of MeerKAT observations. 2009.003 (Astrophysics Source Code Library, 2020).
van Straten, W. & Bailes, M. DSSPR: digital signal processing software for pulsar astronomy. Astron. Soc. Aust. 28, 1–14 (2011).
Hotan, A. W., van Straten, W. & Manchester, R. N. PSRCHIVE and PSRFTS: an open approach to pulsar data panel data storage and analysis. Astron. Soc. Aust. 21, 302–309 (2004).
Morello, V. et al. The high time resolution universe survey—XIV. Discovery of 23 pulsars through GPU-accelerated preprocessing. Mon. Not. R. Astron. Soc. 483, 3673–3685 (2019).
Hobbs, G. B., Edwards, R. T. & Manchester, R. N. TEMPO2, a new pulsar-timing package—I. An overview. Mon. Not. R. Astron. Soc. 369, 655–672 (2006).
Boriakoff, V. Pulsar AP 2016+28: high-frequency periodicity in the pulse microstructure. Astrophys. J. Lett. 208, L13–L16 (1976).
Lyne, A. & Graham-Smith, F. Pulsar Astronomy (Cambridge University Press, 2012).
Lange, C., Kramer, M., Wielebinski, R. & Jessner, A. Radio pulsar microstructure at 1.41 and 4.85 GHz. Astron. Astrophys. 332, 111–120 (1998).
Coates, J. D., Weissberg, J. M. & Hawkins, T. H. Quasiperiodic microstructure in radio pulse emission. Astron. J. 100, 1882–1891 (1991).
Mitra, D., Basu, R., Melikidze, G. I. & Arjunwadkar, M. A single spark model for PSR J2144-3933. Mon. Not. R. Astron. Soc. 492, 2468–2480 (2020).
Watts, A. L. et al. Colloquium: measuring the neutron star equation of state using X-ray timing. Rev. Mod. Phys. 88, 021001 (2016).
Evans, P. A. et al. GRB sample statistics from a uniform, automatic analysis of XRT data. In American Institute of Physics Conference Series Vol. 1133 (eds Meegan, C. et al.) 46–48 (American Institute of Physics, 2009).

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Author contributions
M.C. and BWKS drafted the manuscript with suggestions from co-authors. M.C. is the PI of the MeerKAT DDIT and Parkes data. BWKS is the PI of the MeerTRAP data and R.F. and PWoudt are the PIs of the ThunderKAT data. M.C. reduced and analysed 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.E.M. performed the Swift analysis. D.B., J.B. and P. Woudt obtained and analysed data from the SALT and South African Astronomical Observatory 1-m telescopes. 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.

Competing interests
The authors declare no competing interests.

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Extended Data Fig. 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 1σ. We used the L-band MeerKAT data for the timing analysis. The light coloured data points are from the Parkes UWL observations.
Extended Data Fig. 2 | Examples of quasi-periodic pulses. The top two rows show pulse profiles and their corresponding ACFs at 306.24 μs 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 Fig. 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 Fig. 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 Fig. 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 the Snapshot Imaging section of the Methods for details.
Extended Data Fig. 6 | See next page for caption.
Extended Data Fig. 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 Fig. 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 μJy 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.