Sub-second periodicity in a fast radio burst

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1 Sub-second periodicity in a fast radio 2 burst

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17 The origin of fast radio bursts (FRBs)¹, millisecond-duration flashes of radio
 18 waves that are visible at distances of billions of light-years, remains an open
 19 astrophysical question.² Here we report the detection of the multi-component
 20 FRB 20191221A with the Canadian Hydrogen Intensity Mapping Experi-
 21 ment Fast Radio Burst Project (CHIME/FRB), and the identification of a pe-
 22 riodic separation of 216.8(1) ms between its components with a significance
 23 of 6.5σ . The long (~ 3 s) duration and nine or more components forming
 24 the pulse profile make this source an outlier in the FRB population. We
 25 also report two additional FRBs, 20210206A and 20210213A, whose multi-
 26 component pulse profiles show some indication of periodic separations of
 27 2.8(1) and 10.7(1) ms, respectively, suggesting the possible existence of a group
 28 of FRBs with complex and periodic pulse profiles. Such short periodicities
 29 provide strong evidence for a neutron-star origin of these events. More-
 30 over, our detections favour emission arising from the neutron-star magne-
 31 tosphere,³ as opposed to emission regions located further away from the star,
 32 as predicted by some models.⁴ Possible explanations for the observed period-
 33 icity include super-giant pulses from a neutron star that are possibly related
 34 to a magnetar outburst and interacting neutron stars in a binary system.

35 Operating on the Canadian Hydrogen Intensity Mapping Experiment (CHIME)
 36 radio interferometer located at the Dominion Radio Astrophysical Observatory in
 37 Canada, CHIME/FRB⁵ is an ongoing experiment to find and study a large num-
 38 ber⁶ of FRBs. CHIME is a cylindrical North-South oriented transit radio inter-
 39 ferometer observing in the 400–800-MHz range. Upon detection of an FRB, the

so-called *intensity* data, i.e. the total intensity of the signal as a function of time and frequency, are stored. Additionally, channelized complex voltages (referred to as *baseband* data) with full polarisation information are stored for a subset of FRBs.⁷ Details of these two data formats are reported in the Methods.

In a small fraction of events detected by CHIME/FRB ($\lesssim 0.5\%$),⁶ five or more separate components are visible in the pulse profiles obtained by summing all frequency channels of an intensity dataset after correcting for the effects of the dispersion measure (DM). Three of these multi-component FRBs show a regular separation between the single components of their pulse profiles (Figure 1). Particularly striking is FRB 20191221A, with a total duration of roughly three seconds and at least nine overlapping components. No other FRB candidate observed by CHIME/FRB contains a comparable or greater number of sub-components. Two other notable sources are FRBs 20210206A and 20210213A, formed by five and six components, respectively. While only intensity data was stored for FRB 20191221A, both intensity and baseband data are available for FRBs 20210206A and 20210213A. The properties of the three bursts are reported in Table 1.

We performed a Fast Fourier Transform (FFT) on the three FRB pulse profiles. Significant peaks in the resulting power spectra are clearly visible in Figure 2, indicating a possible periodicity in the times of arrival (ToAs) of components in the pulse profile of each burst. For each burst, individual sub-components have been fitted with a Gaussian function convolved with an exponential to account for likely scattering (using the same scattering timescale for all the components, see Methods). The average width of single components and the exponential time

constant for each burst are reported in Table 1. The resulting ToAs have been used to perform a timing analysis around the initial period derived from the power spectra, also shown in Figure 2. Refined periods obtained from the timing analysis are reported in Table 1.

Since the power spectrum alone does not provide a good figure of merit if a time series contains a small number of components with varying intensity, we calculated the significance of the periodicity for the three bursts by simulating a distribution of random ToAs, as described in the Methods. The significance found for FRB 20191221A is 6.5σ , corresponding to a spurious detection probability of 6.7×10^{-11} . Therefore, we consider the measured periodicity of 216.8(1) ms robust with high confidence. On the other hand, the significance of the periodicities measured for FRBs 20210206A and 20210213A are only 1.3 and 2.4σ , corresponding to spurious detection probabilities of 0.2 and 0.02, respectively. Therefore, we consider the periodicities of 2.8(1) and 10.7(1) ms detected in these two bursts to be only suggestive. However, these FRBs demonstrate the existence of a distribution in the number of components in burst profiles, with some sources having a large number of components, and possible periodic separations. Another possible periodic separation in the multiple components of the repeating FRB 20200120E has recently been presented,⁸ strengthening this hypothesis.

A periodicity in the activity level of two FRBs has been previously reported with periods of 16.3 and 157 days, respectively.^{9,10} However, such a periodicity does not represent an actual time delay between subsequent bursts, and thus, also given the different timescales, we do not consider the two phenomena to be re-

lated.

Millisecond to second periodicities may suggest that the bursts are generated by Galactic radio pulsars that have been misidentified as extragalactic. However, FRB 20191221A, whose multiple components have the highest periodic significance, has a measured DM ~ 4 times larger than the maximum value expected by models of the Milky Way electron content.^{11,12} The DM of FRB 20210213A is ~ 10 times the expected Galactic contribution. FRB 20210206A, located at a Galactic latitude $b = -2.5$ deg, has a DM ~ 1.5 times larger than the Galactic contribution, making its extragalactic nature less certain given the larger uncertainty of models at low latitudes.¹³ We searched for evidence of ionized^{14,15} or star-forming¹⁶ regions in the direction of the three FRBs that could account for the excess DM but found none. We conclude that the FRBs are extragalactic with high probability, especially FRBs 20191221A and 20210213A, which are located at high Galactic latitudes.

None of the three FRB sources presented here has yet been seen to repeat on longer timescales. Specifically, we determined that no additional bursts have been detected up to March 10th, 2021 above an S/N of 9 at a position consistent within $\Delta\text{RA} = 2.2 \text{ deg } \cos^{-1}(\text{Dec})$ and $\Delta\text{Dec} = 1 \text{ deg}$ of these three sources using an algorithm based on density-based spatial clustering of applications with noise (DBSCAN).^{17,18} The nominal DM range threshold for the clustering was set to 13 pc cm^{-3} , corresponding to the largest DM uncertainty in the real-time pipeline of CHIME/FRB.⁵

Multi-component bursts that are associated with repeating sources of FRBs of-

109 ten exhibit downward-drifting subbursts,^{19–21} but these three bursts show a similar
 110 spectrum for all of their components, suggesting that they might represent a differ-
 111 ent sub-population of FRBs. The spectrum of FRB 20191221A is affected by the
 112 telescope response, mainly due to the detection at a location offset from the cen-
 113 tre of a formed beam, which produces strong bandpass effects, as summarized in
 114 the Methods.²² We did not attempt to correct for this effect given the uncertainty
 115 on the localization. In contrast, baseband data available for FRBs 20210206A
 116 and 20210213A allowed us to localize the sources with sufficient precision to
 117 form beams in these directions and, therefore, limit the effect of their bandpass,⁷
 118 leaving only the much less prominent bandpass of the telescope primary beam.⁵
 119 Therefore, the lack of emission above ~ 500 MHz seen for FRB 20210213A is
 120 astrophysical.

121 Our modeling of the pulse profile of FRB 20191221A, visible in Fig. 3 and
 122 described in detail in the Methods, shows that its single components have a rela-
 123 tively narrow width of 4(1) ms, even though they overlap due to a large scattering
 124 timescale $\tau_s = 340(10)$ ms at 600 MHz. Although these estimates may be affected
 125 by unresolved features in the profile mimicking an exponential decay, it is clear
 126 that the FRB emission experienced strong scattering, significantly in excess of the
 127 Galactic contribution expected given its sky position.¹¹ It is worth noting that all of
 128 the emission from this FRB is consistent with single components overlapping due
 129 to the large scattering and no envelope of emission is required in our fit, whose
 130 residuals are consistent with noise, as is visible in Fig. 3. The other two FRBs
 131 show narrower widths and much shorter scattering timescales (see Table 1).

132 An analysis of the polarisation properties has been performed for the bursts
 133 with baseband data, FRBs 20210206A and 20210213A. A rotation measure (RM)
 134 of $+193.6 \pm 0.1 \text{ rad m}^{-2}$ has been measured for FRB 20210206A. We estimate
 135 a Galactic RM contribution of $\text{RM}_{\text{MW}} = -150 \pm 33 \text{ rad m}^{-2}$ along the sightline
 136 of FRB 20210206A,²³ suggesting a significant extragalactic source of Faraday ro-
 137 tation. The corresponding polarisation profiles and polarisation angle (PA) curve
 138 are presented in Figure 4. On the other hand, FRB 20210213A appears to be un-
 139 polarized. Possible reasons for this are discussed in the Methods, together with a
 140 detailed description of the polarisation analysis.

141 Leading theories for the origin of FRBs are related to magnetars.² Indeed, a
 142 bright pulse has been detected from a Galactic magnetar whose properties are
 143 compatible with FRBs.^{24,25} There are two main classes of magnetar models to
 144 explain FRBs: the emission is either generated in the star’s magnetosphere or
 145 triggered in plasma regions local to the magnetar by a flare of the star. The de-
 146 tection of periodicity is naturally explained by the first class of magnetar models,
 147 and it has been extensively observed in Galactic neutron stars, albeit with orders
 148 of magnitude lower luminosities.²⁶ By contrast, the second class of models does
 149 not intrinsically predict a millisecond modulation in the emitted signal and, thus,
 150 would require *ad hoc* assumptions to explain the observed behaviour. Also, some
 151 of these models predict a constant polarisation angle⁴ and are thus disfavoured by
 152 the swing observed for FRB 20210206A.

153 The periodic structures in the bursts could be explained by a rotating neutron
 154 star with beamed emission similar to Galactic radio pulsars where, for an unknown

155 reason, a train of single pulses has an abnormally high luminosity for a short pe-
 156 riod of time. The period and jitter in the ToAs observed for FRB 20191221A
 157 are compatible with those seen in Galactic pulsars.²⁶ On the other hand, if the
 158 periodicities reported for FRBs 20210206A and 20210213A are real, the larger
 159 jitters observed are more similar to the values measured for Galactic radio mag-
 160 netars.^{27–30} For example, FRBs 20210206A and 20210213A both have observed
 161 periodicities (see Extended Data Table 2) that are comparable to the characteristic
 162 delay time between successive radio pulse components measured from the Galac-
 163 tic Centre magnetar, PSR J1745–2900, over many rotational cycles.²⁹ In the case
 164 of the Galactic Center magnetar, it is not evident that this characteristic timescale
 165 is related to the magnetar’s rotational period.²⁹

166 Alternatively, bright radio pulsars and magnetars sometimes show micro-structures
 167 in some of their single pulses with profiles that are similar to those of the FRBs
 168 reported on here.^{28,29,31–33} Some of the micro-structures, possibly generated by
 169 temporal variations in the emission beam,³² show quasi-periodic separations³⁴ that
 170 could be related to the rotation period of the neutron star.³² However, if the sin-
 171 gle components of FRB 20191221A are generated by a similar mechanism, the
 172 total pulse width would be ~ 3 seconds, ~ 4 times larger than the widest compo-
 173 nent ever observed in a Galactic radio pulsar.²⁶ Also, as opposed to typical micro-
 174 structures seen in pulsars, the components of the three FRBs here presented do not
 175 require an envelope of emission and the signal can be modeled as coming from
 176 single components, even when they overlap due to scattering (Figure 3). How-
 177 ever, the varying but continuous PA curve of FRB 20210206A argues in favor of

178 a common envelope of emission rather than distinct single pulses in pulsar-like
179 emission.

180 Recent theories have also predicted the detection of periodicity in FRB sub-
181 bursts if magnetar crustal oscillation frequencies can be directly related to oscilla-
182 tion modes on the surface of the magnetar during outburst,³⁵ similar to the quasi-
183 periodic oscillations seen in X-rays for Galactic magnetars.³⁶ For the bursts in this
184 sample, periodicities of 2.8–216.8 ms correspond to surface oscillation frequen-
185 cies of 357–4.6 Hz, within the range observed previously in Galactic magnetars.³⁶

186 One possible scenario to explain the larger radio luminosity of these bursts
187 compared to those observed thus far in the Galaxy is that they could represent the
188 observation of a gravitationally micro-lensed extragalactic pulsar. In this model,
189 pulses from a pulsar in a binary system are magnified in intensity by the gravita-
190 tional field of its companion. In the Methods, we consider a radio pulsar with an
191 average luminosity placed at 1 Gpc (approximately the DM-inferred distance of
192 FRB20210213A) and find that a companion with a mass of at least $10^6 M_\odot$ and an
193 orbital separation of 3 – 30 pc can provide both the magnification and transit time
194 needed to explain the observations. However, the alignment angle is required to be
195 smaller than 10^{-17} – 10^{-18} arcseconds, which implies a low probability to observe
196 such an event despite the large trial factor provided by the number of galaxies
197 within a Gpc distance. In addition, in this scenario, we would expect to detect a
198 larger number of FRBs from gravitationally lensed pulsars in the nearby universe
199 since they would require a lower magnification. Therefore, the absence of multi-
200 peaked, periodic FRBs with a small DM excess⁶ implies that it is unlikely that

201 we have detected a gravitationally micro-lensed pulsar of average luminosity at a
202 distance of 1 Gpc.

203 In a different theory, the single components of periodic FRBs could be gener-
204 ated by the magnetospheric interaction of merging neutron stars, either through a
205 unipolar inductor process^{37–40} or magnetic braking and spin-orbital synchroniza-
206 tion.^{41,42} In such a case, FRB emission may show multiple peaks corresponding to
207 a favourable orbital phase for a range of orbital periods. The magnetospheres of
208 the neutron stars may interact long before their mergers to produce FRBs, leading
209 to periodicity timescales of tens of milliseconds to a few hundred seconds.⁴³ Near
210 the time of the merger, the orbital period of the binary changes rapidly due to the
211 loss of angular momentum through gravitational wave radiation. As described in
212 the Methods, we fit the ToAs of these events as passages of a pre-merger binary
213 system through a constant orbital phase with respect to our line of sight by varying
214 the initial phase and binary masses. With a possible periodicity of 2.8 ms, FRB
215 20210206A cannot be explained by a merging neutron star model as the expected
216 period derivative $\dot{P} \sim 5 \times 10^{12} \text{ s s}^{-1}$ is not consistent with the observed peak
217 separation. However, the longer periodicity timescales of FRBs 20191221A and
218 20210213A allow for much smaller period derivatives and they are compatible
219 with merging binary systems containing a neutron star. A future detection of an
220 additional burst from these sources would rule out this model.

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Parameter	20191221A	20210206A	20210213A
MJD*	58838.20638077, 58838.20630684	59251.11021004	59258.46924637
Baseband data	N	Y	Y
RA* J2000 (deg)	44.6(1), 38.4(2)	53.86(2)	192.6(1)
Dec* J2000 (deg)	79.74(2), 79.73(3)	52.743(7)	83.28(2)
l^* (deg)	128.60(2), 127.56(4)	146.359(9)	122.97(2)
b^* (deg)	18.30(2), 17.78(3)	−2.503(8)	33.85(2)
DM (pc cm ^{−3})	368(6)	361.35(7)	482.5(2)
Period (ms)	216.8(1)	2.8(1)	10.7(1)
Period significance (σ)	6.5	1.3	2.4
Average width (ms)	4(1)	0.068(5)	0.42(4)
Scattering (ms)	340(10)	1.25(2)	0.78(5)
Fluence [†] (Jy ms)	$1.2(4) \times 10^3$	47(14)	8.4(2.9)
Peak Flux [†] (Jy)	2.0(1.0)	5.7(1.8)	1.2(5)
Exposure [¶] (hours)	340.1(2), 106(4)	99.2(1)	196(4), 496.7(2)

* Two localization regions are equally probable for FRB 20191221A, both positions are reported.

[†] Reported fluence and flux for FRB 20191221A are lower limits. See Methods for details on their calculation.

[¶] For circumpolar sources ($\delta > +70^\circ$), the two entries correspond to exposure in the upper and lower transit, respectively.

Table 1: **Properties of FRBs 20191221A, 20210206A, 20210213A.** Uncertainties are reported at the 68.3% confidence level. The arrival time is that of the brightest sub-burst at the Solar System’s barycentre and infinite frequency. The sky position has been obtained from baseband data whenever available. The DM is calculated to maximize the peak S/N in the timeseries. The scattering timescale is referenced to the centre of the band, i.e. ~ 600 MHz. Fluence is for the full band-averaged profile, and peak flux is the maximum in the profile (with 1-ms time resolution).

Figure 1: **Signal intensity as a function of time and frequency (“waterfall plots”) for three multi-component bursts detected by CHIME/FRB.** Panels a, b and c show FRBs 20191221A, 20210206A and 20210213A, respectively. In all plots, effects of dispersion have been removed, data have been averaged to 3.125 MHz frequency resolution and to time resolutions of 7.86432 ms, 81.92 μ s and 163.84 μ s, respectively. Missing or masked (due to radio frequency interference) frequency subbands are replaced with off-burst median values and are indicated with a red square near the vertical axis. Displayed on top of each panel are the time series averaged over the bandwidth with detected signal for each FRB, i.e., 600–800, 400–800 and 400–450 MHz, respectively.

Figure 2: **Periodicity analysis of the FRBs.** *Left*, power spectrum obtained with a discrete Fourier Transform of the pulse profiles. Vertical dotted lines represent the period found with the timing analysis. *Middle*, residuals of a timing analysis to refine the period. Times of arrival (TOAs) relative to the first value are represented with dots. 1σ error bars are often smaller than the symbol size. Horizontal dashed lines indicate a phase of 0 around which residuals have been rotated. *Right*, study of the statistical significance of the measured periodicities by using a periodicity-sensitive score $\hat{S}$, described in the Methods. The grey histograms have been obtained with an ensemble of simulations, whereas the values measured for the three bursts are represented with vertical dotted lines.

Figure 3: **Modeling of the pulse profile of FRB 20191221A.** The measured pulse profile is plotted in black with a time resolution of 7.86432 ms for visual purposes (the full resolution data at 0.98304 ms have been used to obtain the values presented in Table 1). The Gaussian function convolved with an exponential used to model nine peaks in the profile is plotted in red, and peak locations are highlighted by vertical lines. Fit residuals are shown in the bottom panel with a red horizontal line at zero residual.

Figure 4: **Polarisation profiles for FRB 20210213A.** Panel A: the total (black), linear (red) and circular (blue) intensities across the burst envelope. Panel B: The linear polarised fraction. Panel C: The polarisation angle (PA) values with 1σ error bars rotated by an arbitrary angle.

314 **Methods**

315 **1 CHIME/FRB sensitivity beams**

316 The CHIME radio telescope is a transit interferometer formed by 1024 dual-
317 polarisation antennae observing in the 400-800 MHz range. The field of view
318 of single antennae summed together incoherently is defined as the primary beam
319 of the telescope, whose FWHM sensitivity spans ~ 110 degrees in the N-S direc-
320 tion and 1.3 (2.5) degrees the E-W direction at the top (bottom) of the observing
321 bandwidth.⁵ The telescope antennae can be added coherently to produce a *formed*
322 (or *synthesized*) beam in one or more directions and increase the telescope sen-
323 sitivity towards those directions. Formed beams have a size between ~ 0.3 and
324 0.7 degrees, depending on the observing frequency and zenith angle.⁵ Therefore,
325 their sensitivity and bandpass vary spatially more rapidly than those of the primary
326 beam.

327 In the real-time search for FRBs, 1024 beams are formed on the sky within the
328 primary beam via an FFT (FFT beams).⁴⁴ The total intensity measured by these
329 FFT beams as a function of time and frequency is referred to as *intensity* data.
330 Intensity data have a time resolution of 0.98304 ms and are divided into 16,384
331 channels. Additionally, for a part of the detected FRBs, ~ 100 ms of *baseband*
332 complex voltages are also stored.⁵ The baseband data have a time resolution of
333 $2.56 \mu\text{s}$, are divided into 1024 frequency channels and contain full polarisation
334 information. Thanks to the phase information available in baseband data, synthe-
335 sized beams can be formed to virtually any position on the sky.

2 Properties of the bursts

Sky localization of bursts with intensity data. To localize an FRB with CHIME/FRB intensity data, we fit the spectra of the burst detected in different formed beams with a model of the CHIME/FRB beams and an underlying burst spectrum using a Markov chain Monte Carlo (MCMC) method.⁴⁵ The model of the CHIME/FRB beams contains a description of both the synthesized^{44,46} and primary⁶ (i.e. telescope) beams and the underlying spectrum is modeled as a Gaussian. The free parameters are therefore width, mean, and amplitude of the underlying Gaussian model spectrum, along with the sky position. We use a flat prior on the position of the event that spans 5° to either side of meridian in E-W, while in N-S the prior spans the extent of the beams that detected the event. The position and uncertainties are derived from the 2D posterior distribution (in ‘x’, the E-W coordinate, and ‘y’, the N-S coordinate) marginalized over the parameters of the Gaussian spectral model. The best-fit position is used as an initial guess in the baseband localization. Since FRB 20191221A did not have baseband data available, the position reported in Table 1 is derived from the intensity localization described in the present section. The posterior probability distribution is double-peaked in the E-W direction and so two positions are reported for the event.

Sky localization of bursts with baseband data. A detailed description of the algorithm used to obtain the sky position of FRBs by using baseband data has been presented elsewhere.⁷ In summary, a grid of partially overlapping beams is produced around the intensity localization and a total S/N value is calculated in each beam. The resulting intensity map of the signal is fitted with a mathematical

359 model describing the telescope response to determine the source position. The
360 localization and its uncertainties have been calibrated with a sample of sources
361 with a known position to account for any unmodelled systematics.⁷

362 **Calculation of the fluence and flux.** Flux and fluence calculations are deter-
363 mined using the intensity data for each burst with the same method presented in
364 previous CHIME/FRB papers.^{9,21,22,47–49} In summary, meridian transits of steady
365 sources with known spectra are used to sample the conversion between beam-
366 former units and Janskys as a function of frequency across the N-S extent of the
367 primary beam. For each burst, the beamformer to Jansky conversion closest in
368 zenith angle (assuming N-S symmetry) is applied to the intensity data to obtain
369 a dynamic spectrum in physical units roughly corrected for N-S primary beam
370 variations. Fluence values are obtained from integrating the burst extent in the
371 band-averaged time series, and peak flux values are taken to be the maximum
372 value within the burst extent (at 0.98304 ms resolution). Uncertainties are esti-
373 mated using steady source observations.

374 The calibration procedure described above does not correct for burst attenu-
375 ation due to the synthesized beam pattern and E-W primary beam profile. Flu-
376 ences and fluxes derived from this method are best interpreted as lower limits,
377 with an uncertainty on the limiting value. This is what we report in Table 1 for
378 FRB 20191221A. However, for bursts that have a baseband localization, we can
379 achieve more realistic fluence results by using the beam model to scale between
380 the location of the calibrator at the time of transit and the location of each FRB.
381 This is what we report in Table 1 for FRBs 20210206A and 20210213A.

382 **Calculation of the exposure.** The exposure of the CHIME/FRB system to the
383 sources reported in this work was determined for the interval from August 28,
384 2018 to March 1, 2021. For each source, the exposure is calculated by summing
385 the duration of daily transits across the FWHM region of the synthesized beams at
386 600 MHz. Two of the three sources, having declinations $> +70^\circ$, transit through
387 the primary beam twice per day. These sources have their upper and lower tran-
388 sit exposures calculated separately as the beam response for the two transits is
389 different.

390 While calculating the total exposure, we include daily transits for which the
391 CHIME/FRB detection pipeline was fully operational, which is determined using
392 recorded system metrics. Transits occurring on days when the detection pipeline
393 was being tested or upgraded are not included. Additionally, system sensitivity
394 varies on a day-to-day basis due to daily gain calibration as well as changes in
395 the detection pipeline and the RFI environment. We evaluate the variation in sen-
396 sitivity for each sidereal day using observations of 120 Galactic pulsars with the
397 CHIME/FRB system.^{21,48} For each source, transits for which the sensitivity varied
398 by more than 10% from the median in the aforementioned observing interval are
399 excised from the total exposure. On average, the observing time corresponding to
400 the excised transits amounted to 4% of the exposure for each source.

401 The uncertainty in the source declination is a source of error in the measure-
402 ment of the exposure. The source declination dictates where the transit path cuts
403 across a synthesized beam with the transit duration being maximum if the path
404 crosses the beam centre and zero if the path lies between two beams.⁴⁹ We es-

405 timate the resulting uncertainty in the exposure by generating a uniform grid of
406 positions within the 68% confidence localization region for each source. The re-
407 ported exposure in Table 1 is the average for these sky positions with the error
408 corresponding to the standard deviation.

409 **3 Modeling of pulse profiles**

410 **FRB 20191221A** has a duration of ~ 3 seconds and is composed of multiple
411 peaks overlapping due to a large broadening caused by scattering. To properly
412 calculate the periodic separation among its components, it is important to avoid
413 human bias in selecting significant peaks in the pulse profile. We reduced human
414 bias in the following way. First, we smoothed the pulse profile using the Savitzky-
415 Golay filter as implemented in `SciPy`.¹ The filter requires two input parameters,
416 the window length, and the polynomial order. We explored the full parameter
417 space of the two parameters up to a window of 600 ms and a polynomial order
418 of 12. For each combination, separate peaks in the smoothed pulse profiles were
419 identified from local maxima if the peaks were wider than 3 bins to avoid noise
420 spikes. One example of this procedure is reported in Extended Data Figure 1.

421 We grouped together different combinations of parameters yielding the same
422 number of peaks, noting their location in the profile and excluding values lower
423 than 7 and higher than 14 peaks as visually implausible. For each value of the
424 peak number between 7 and 14, the different peak locations resulting from each of
425 the initial parameter combinations were grouped with a kernel density estimator,

¹<https://scipy.org/>

426 varying its window until we obtain the expected number of peaks. We apply this
 427 method to obtain seven combinations of initial peak positions composed of 7 to
 428 14 peaks. We model each peak using the exponentially modified Gaussian (EMG)
 429 described by^{6,50}

$$f(t; \mu, w, \tau) = \frac{A}{2\tau} \exp\left(\frac{\mu - t}{\tau} + \frac{2\sigma^2}{\tau^2}\right) \operatorname{erfc}\left(\frac{(\mu - t)\tau + w^2}{w\tau\sqrt{2}}\right), \quad (1)$$

430 where erfc is the complementary error function, A is the signal amplitude, μ and
 431 w are the Gaussian mean and width, respectively, and τ is the scattering timescale.
 432 For each number of peaks, the pulse profile is modelled with a sum of one EMG
 433 function per peak through an MCMC sampling using `emcee`⁴⁵ with wide uni-
 434 form priors for all parameters. The scattering timescale is set to be the same for
 435 all peaks, while the other parameters are allowed to vary. The resulting χ_{red}^2 val-
 436 ues, presented in Extended Data Figure 2, are used to select the number of peaks
 437 yielding the best model. We estimate the minimum variation in the χ_{red}^2 value that
 438 we can measure confidently given the number of free parameters N as

$$\sigma = \sqrt{\frac{2}{N}}. \quad (2)$$

439 As visible in Extended Data Figure 2, the model with 9 components has the small-
 440 est χ_{red}^2 that deviates significantly from the previous values. Therefore, we choose
 441 this as the best model to reproduce the data and use its parameters in our analysis.
 442 As discussed in Section 5 of the Methods, choosing a different number of peaks
 443 in the profile leads to values of the significance of the periodicity that are still very

444 high, especially for peaks between 9 and 12.
445 **FRBs 20210206A and 20210213A** The components in these two events do not
446 overlap. Therefore, it was not necessary to perform the method described above.
447 Instead, we directly used the locations of the peaks in the smoothed profiles as
448 initial conditions for the MCMC sampling using the same model described above.
449 The scattering timescale and average width of the resulting models are presented
450 in Table 1 for the three FRBs, while the peak positions relative to the first one in
451 each profile are reported in Extended Data Table 1.

452 **4 Timing analysis**

453 The periodicities of the three FRBs reported here were first investigated through
454 a power spectrum of the pulse profile. This has been computed as the absolute
455 square of the Fast Fourier Transform (FFT) of the pulse profiles. The FFT has been
456 calculated with the implementation offered by the `SciPy` module. The resulting
457 power spectra presented in Figure 2 show clear peaks for the three sources. The
458 periods corresponding to the most prominent peaks in the power spectra have
459 been refined through an additional timing analysis. We ran a least-squares fit
460 as implemented in `SciPy` using a simple model with the period as the only free
461 parameter, calculating residuals as the modulo of ToAs (reported in Extended Data
462 Table 1) and the period. The results of these fits are the values reported in Table 1.

5 Significance of the periodicity

The following steps were used to estimate the significance of the periodicity calculated for each of the three sources and reported in Table 1.

1. For each event, we use the ToAs reported in Extended Data Table 1 to compute a statistic $\hat{S}$ which is sensitive to periodicity. The construction of $\hat{S}$ is described below.
2. To assign a statistical significance, we use a frequentist approach. We evaluate the statistic $\hat{S}$ on simulated events and rank the ‘data’ value $\hat{S}_{\text{data}}$ within the ensemble of simulated values $\hat{S}_{\text{sim}}$, obtaining a p -value. The results are summarized in Extended Data Table 2.
3. For FRB 20191221A, there is an extra step. With 10^8 simulations, we find that none of the $\hat{S}_{\text{sim}}$ values exceed $\hat{S}_{\text{data}}$. This shows directly that the level of periodicity in this 9-component event is extraordinarily unlikely to occur by random chance. To assign a p -value, we fit an analytic model PDF to the tail of the $\hat{S}_{\text{sim}}$ distribution and integrate the model PDF.

In the rest of this section, we describe the details in the above steps.

Definition of $\hat{S}$. To motivate the definitions which follow, consider Extended Data Figure 3. Each point is one pulse in the 9-component event, with the ToA t_i on the y -axis. The values on the x -axis are the 9-element integer-valued vector

$$n_i = (0, 2, 3, 5, 7, 8, 9, 10, 12) \quad (3)$$

482 Periodicity appears in Extended Data Figure 3 as the points falling nearly on a
 483 straight line. Note that there are four ‘gaps’ in this example, i.e. pulse periods
 484 where no pulse is observed (either because it is physically absent or buried in the
 485 noise). Each gap is represented by consecutive entries in n_i which differ by 2
 486 (rather than 1).

487 Based on this picture, we construct statistics as follows. For a fixed choice of
 488 gap vector n_i , we fit the points (n_i, t_i) in Figure 3 to a straight line

$$t_i = f^{-1}n_i + T_0 + r_i \quad (4)$$

489 where this equation defines the residuals r_i , and the parameters (f, T_0) have been
 490 chosen to minimize $\sum_i r_i^2$. Note that this fitting procedure weights all ToAs
 491 equally, and does not use statistical errors on ToAs given the large jitter observed.

492 We define a statistic

$$\hat{L}[n] = \frac{1}{2} \log \left(\frac{\sum_i (t_i - \bar{t}_i)^2}{r_i^2} \right) \quad (5)$$

493 By construction, $\hat{L}[n]$ measures the extent to which the points fall on a straight line
 494 for a fixed choice of gap vector n_i . We define the periodicity-sensitive statistic $\hat{S}$
 495 by trying all possible values of n_i

$$\hat{S} = \max_n \left(\hat{L}[n] \right) \quad (6)$$

496 The maximum in the equation is taken over all trial gap vectors n_i with $\leq G$
 497 gaps, where G is an input parameter to the pipeline. More formally, we take

the maximum over integer-valued vectors n_i such that $n_i = 0$, $n_{i-1} < n_i$, and $n_p < n_1 + p + G$, where $p = \text{len}(n)$ is the number of pulses. The number of such vectors is

$$N_{\text{trials}} = \binom{G + p - 1}{G} \quad (7)$$

By default, we choose $G = N_{\text{gaps}} + 1$, where N_{gaps} is the number of gaps that are empirically seen in each event. This is a conservative choice, which deliberately ensures that N_{trials} is a few times larger than the value obtained with $G = N_{\text{gaps}}$ (see Extended Data Table 2).

Procedure for simulating ToAs. Our simulation procedure has two parameters: a mean spacing $\bar{d}$, and a dimensionless ‘exclusion’ parameter $0 \leq \chi \leq 1$ defined by

$$\chi = \frac{\text{Minimum allowed spacing between pulses}}{\text{Mean spacing } \bar{d} \text{ between pulses}}. \quad (8)$$

We simulate a sequence $t_1 < \dots < t_p$ of ToAs by independently randomly generating arrival time differences $d_i = (t_i - t_{i-1})$ from the uniform probability distribution $p(d)$ defined by

$$p(d) = \begin{cases} 1/(2\bar{d} - 2\chi\bar{d}) & \text{if } \chi\bar{d} \leq d \leq (2 - \chi)\bar{d} \\ 0 & \text{otherwise} \end{cases}. \quad (9)$$

We also tried an exponential distribution, but find that it gives lower p -values (higher significance). To be conservative, we use the uniform distribution throughout. When we assign a statistical significance by ranking $\hat{S}_{\text{data}}$ within a histogram

514 of $\hat{S}_{\text{sim}}$ values, we find that the value of $\bar{d}$ does not affect the statistical signifi-
 515 cance, while the statistical significance decreases as χ is increased in the simula-
 516 tions. However, the statistical significance is not strongly dependent on χ for a
 517 reasonable range of the parameter. Therefore, we choose $\chi = 0.2$ to represent our
 518 analysis.

519 **Tail-fitting procedure.** For FRB 20191221A, there is an extra step. With 10^8
 520 simulations, we find that none of the $\hat{S}_{\text{sim}}$ values exceed $\hat{S}_{\text{data}}$. Therefore, we fit
 521 the 10^5 largest values S_i of the $\hat{S}_{\text{sim}}$ -distribution to an analytic PDF of the form

$$p(S) \propto e^{-aS^q} \quad (10)$$

522 by maximizing the likelihood $\prod_i P(S_i|a, q)$. The analytic PDF $p(S)$ is an excel-
 523 lent visual fit to the tail of the $\hat{S}_{\text{sim}}$ distribution. More quantitatively, a KS test
 524 shows no statistical difference between $p(S)$ and the simulations (p -value 0.58).
 525 To assign a bottom-line p -value, we integrate the analytic PDF from $S = \hat{S}_{\text{data}}$ to
 526 $S = \infty$. This gives a p -value of 6.7×10^{-11} , corresponding to Gaussian signifi-
 527 cance 6.5σ .

528 **Optimality.** The preceding derivation of the statistic $\hat{S}$ was heuristic, based on
 529 intuition from Extended Data Figure 3. However, $\hat{S}$ can also be interpreted as a
 530 likelihood ratio statistic. This provides a systematic derivation, and also shows
 531 that $\hat{S}$ is near-optimal.

532 Let H_0 be the null hypothesis that the ToAs t_i are Gaussian distributed with
 533 mean T and variance σ^2 . In this model, the conditional likelihood of obtaining

534 ToAs t_i given model parameters (T, σ) is

$$P(t_i|H_0, T, \sigma) = \prod_i \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(t_i - T)^2}{2\sigma^2}\right) \quad (11)$$

535 Let H_1 be the alternate hypothesis that the t_i are given by the linear regression
 536 in Eq. (4), where the residuals r_i are Gaussian with variance σ^2 . The conditional
 537 likelihood of obtaining t_i given model parameters (n_i, f, T, σ) is

$$P(t_i|H_1, n_i, f, T, \sigma) = \prod_i \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(t_i - T - f^{-1}n_i)^2}{2\sigma^2}\right) \quad (12)$$

538 Then a short calculation shows that the $\hat{S}$ statistic is the log-likelihood ratio of the
 539 two models, after maximizing all model parameters

$$\hat{S} = \left(\max_{n,f,t,\sigma} \log P(t_i|H_1, n_i, f, T, \sigma) \right) - \left(\max_{n,f,t,\sigma} \log P(t_i|H_0, T, \sigma) \right) \quad (13)$$

540 **Rayleigh (Z_1^2) Periodicity Analysis.** We have shown in the previous section that
 541 the $\hat{S}$ statistic is nearly optimal for determining the statistical significance of the
 542 periodicity observed in each FRB. However, we also calculated the significance
 543 using a different statistic that is commonly used in studies of periodicities of high-
 544 energy pulsars, the Rayleigh (Z_1^2) statistic^{51,52}. In general, the Z_n^2 test statistic is
 545 defined as:

$$Z_n^2 = \frac{2}{N} \sum_{k=1}^n \left[\left(\sum_{j=1}^N \cos k\phi_j \right)^2 + \left(\sum_{j=1}^N \sin k\phi_j \right)^2 \right], \quad (14)$$

546 where N is the number of ToAs obtained after fitting each burst profile with
 547 Eq. (1), n is the number of harmonics, and ϕ_j is the phase of each ToA, t_j . The
 548 phase of each ToA is determined using $\phi_j = \nu t_j$, where ν is the modulation fre-
 549 quency. In the following analysis, we use $n = 1$ harmonics in Eq. (14), which
 550 corresponds to the Rayleigh test, and the ToAs listed in Table 1. All of the ToAs
 551 were weighted equally in our analysis.

552 We performed a blind search for periodicity using the Z_1^2 test statistic de-
 553 fined in Eq. (14) and the ToAs listed in Extended Data Table 1. The number
 554 of frequency trials used to search for periodicity was determined by the time
 555 resolution (Δt) and the duration (T) of the data containing each of the bursts.
 556 The time resolution and duration of the data used to perform the Rayleigh test
 557 were $\Delta t = 7.86432$ ms and $T = 4.215$ s for FRB 20191221A, $\Delta t = 81.92$ μ s and
 558 $T = 19.6608$ ms for FRB 20210206A, and $\Delta t = 327.68$ μ s and $T = 81.92$ ms for
 559 FRB 20210213A, respectively. We searched for evidence of periodicity by cal-
 560 culating the Z_1^2 test statistics at a range of trial frequencies $\nu \in [\Delta\nu, \nu_{\text{nyq}}]$, where
 561 $\Delta\nu = 1/T$ is the nominal frequency resolution of each data set, $\nu_{\text{nyq}} = \nu_{\text{samp}}/2 = 1/(2\Delta t)$
 562 is the Nyquist frequency, and ν_{samp} is the sampling frequency of the data. In ad-
 563 dition, we oversample the frequency grid by a factor of $\mathcal{O} = 5$. The results of this
 564 calculation are presented in Extended Data Table 2.

565 The values of Z_1^2 for the three events were converted to significance values by
 566 randomly generating arrival time differences using Monte Carlo simulations. Due
 567 to the high significance of the periodicity in FRB 20210213A, we used $\mathcal{N}_{\text{sim}} = 10^{10}$
 568 Monte Carlo simulations in our analysis of this event. For the other two events

569 (FRB 20210206A and FRB 20210213A), $\mathcal{N}_{\text{sim}} = 10^9$ Monte Carlo simulations
 570 were used to determine the significances. Using the measured ToAs, we construct
 571 random realizations of arrival time differences by drawing from a uniform prob-
 572 ability distribution defined by Eq. (9). For each event, we perform separate sets
 573 of simulations for exclusion parameters $0 \leq \chi \leq 0.5$, defined according to Eq. (8).
 574 The value of χ determines the time separation between the simulated ToAs. In the
 575 limit $\chi \rightarrow 1$, the simulated ToAs become perfectly periodic, so we restrict $\chi \leq 0.5$.
 576 These values of χ are used to impose a minimum time separation between ToAs
 577 in the simulations. The statistical significance of the periodicities is not strongly
 578 affected by the choice of these values of χ , so we select $\chi = 0.2$ in this analysis.
 579 We compare the distribution of maximum Z_1^2 test statistics obtained from each set
 580 of simulations, for a given value of χ , to the Z_1^2 value obtained using the measured
 581 ToAs. The false alarm probability (FAP) and equivalent Gaussian significance are
 582 calculated using

$$P_{\text{FAP}} = 1 - \text{CDF}(Z_1^2) = 1 - [1 - P(Z_1^2 > Z_{1,\nu_0}^2 | \nu = \nu_0)], \quad (15)$$

583 where ν_0 is the putative periodicity determined from the ToAs measured from
 584 each event.

585 In this analysis, the tail-fitting procedure described above is not used. In-
 586 stead, the FAPs are calculated based on the number of Monte Carlo simulations
 587 that have a maximum Z_1^2 test statistic which exceeds the Z_1^2 value obtained us-
 588 ing the measured ToAs. In Extended Data Figure 4, we show the distribution of

589 maximum Z_1^2 test statistics from a set of $\mathcal{N}_{\text{sim}} = 10^{10}$ Monte Carlo simulations
 590 performed with $\chi = 0.2$, compared to the measured $Z_1^2 = 17.96$ value obtained for
 591 FRB 20191221A. We find that the periodicity observed from FRB 20191221A has
 592 a significance of 6.22σ using this method. The equivalent significance of the pe-
 593 riodicities observed from FRBs 20210206A and 20210213A are both $< 1\sigma$ using
 594 the Rayleigh (Z_1^2) statistic (see Extended Data Table 2).

595 **6 Polarisation analysis**

596 The polarisation analysis of FRBs 20210206A and 20210213A follows a simi-
 597 lar procedure to that previously applied to other CHIME-detected FRBs.^{21,53} In
 598 particular, an initial RM estimate is made by applying RM-synthesis^{54,55} to the
 599 Stokes Q and U data of each burst. The Stokes spectrum is extracted by integrat-
 600 ing the polarised signal over the burst duration, where time and frequency limits
 601 have been manually adjusted to optimize the RM detection.

602 For FRB 20210206A, RM-synthesis results in an unambiguous RM detection.
 603 This detection is refined by applying a Stokes QU-fitting routine that directly fits
 604 for the modulation between Stokes Q and U from Faraday rotation as well as
 605 the modulation between U and V introduced by an instrumental delay between
 606 the two linear polarisations. Optimal values are determined numerically through
 607 Nested Sampling, a Monte Carlo method that seeks to optimize the likelihood
 608 function given a model and data. Further details on the CHIME/FRB polarisa-
 609 tion analysis pipeline are presented elsewhere.⁵⁶ The instrumental delay, once fit-
 610 ted for, can be used to produce a delay-corrected spectrum. Figure 5 shows the

611 results of RM-synthesis and QU-fitting applied to the delay-corrected spectrum.
 612 The RMs produced from these two independent methods agree within the mea-
 613 surement uncertainties. The RM produced by QU-fitting is used to produce the
 614 polarized burst profile shown in Figure 4.

615 FRB 20210213A, conversely, displays an absence of polarised signal. Apply-
 616 ing RM-synthesis produces no clear RM detection over the range $-2000 \lesssim \text{RM} \lesssim 2000 \text{ rad m}^{-2}$.
 617 For $|\text{RM}|$ values beyond this range, bandwidth depolarisation from Faraday rota-
 618 tion within a single frequency channel becomes significant at the native channel-
 619 ization of CHIME/FRB baseband data.⁷ We developed an algorithm⁵⁶ that em-
 620 ploys a phase-coherent method of correcting for bandwidth depolarisation in data
 621 for which the electric field phase is retained⁵⁷. Using this method, we search
 622 out to $|\text{RM}|$ values as large as 10^6 rad m^{-2} by applying coherent de-rotation to a
 623 sparse grid of trial RMs followed by an incoherent search at neighbouring RM val-
 624 ues. In principle, this method extends detectable RMs to arbitrarily large values.
 625 In practice, artifacts introduced in the channelization of CHIME/FRB baseband
 626 data reduce sensitivity to polarized signals at larger $|\text{RM}|$ values. Given the low
 627 S/N of this burst, it remains possible that this event displays a large $|\text{RM}|$ that
 628 simply goes undetected due to the deleterious effect of the channelization pro-
 629 cedure. We test this possibility by using simulated data to determine the loss of
 630 S/N with increasing RM. Using a simulated burst with properties similar to that
 631 of FRB 20210213A (e.g., S/N, subband), we evaluate the performance of our co-
 632 herent de-rotation algorithm over a range of RM values. We find no significant
 633 loss of polarised signal out to RM values as large as $|\text{RM}| \sim 200,000 \text{ rad m}^{-2}$.

Therefore, if this event does indeed display an RM within this range, a significant fraction of the signal must be unpolarised ($\gtrsim 50\%$) for us to not detect it given the S/N of the event. Conversely, we rule out the possibility of $|\text{RM}|$ values larger than $\sim 200,000 \text{ rad m}^{-2}$ by detecting a lack of splitting in the burst morphology potentially caused by extreme RM values.⁵⁸

We note that ionospheric RM has not been corrected for in our analysis, but it does not exceed a few rad m^{-2} .

7 Model of gravitational lensing

We explore the observability of a pulsar gravitationally micro-lensed. We consider a binary system with a pulsar of mass $M_s = 1 M_\odot$ and explore the parameter space of lensing masses, system alignment, and orbital separations to explain the properties of the three FRBs.

We use a test pulsar at a distance of 1 Gpc emitting periodic pulses with a luminosity of 1 Jy kpc^2 , comparable to Galactic radio pulsars. Without any magnification, such a pulsar would be observed on Earth with a peak flux of $\sim 10^{-11} \text{ Jy}$. Therefore, a magnification $\mu \gtrsim 10^{11}$ is needed to explain the fluxes of $\sim 1 \text{ Jy}$ observed for the three FRBs here reported.

We constrain the space by first requiring the lens mass M_{lens} to be able to magnify the pulsar⁵⁹

$$\mu \lesssim \frac{4\pi G M_{\text{lens}} f}{c^3}, \quad (16)$$

where G is the gravitational constant and f is the observed frequency.

654 The orbital separation of the binary system D_{ls} and its alignment are con-
 655 strained by requiring that we only observe the magnification curve for the dura-
 656 tion of the event Δt . The minimum alignment angle β of the binary system can
 657 be calculated as⁵⁹

$$\mu = \frac{\beta^2 + 2\theta_E^2}{\beta\sqrt{\beta^2 + 4\theta_E^2}}, \quad (17)$$

658 where the Einstein angle θ_E is defined as

$$\theta_E = \sqrt{\frac{4GM_{lens}}{c^2} \frac{D_{ls}}{D_{os}D_{ol}}}, \quad (18)$$

659 where D_{os} is the distance between the observer and the source, D_{ol} is the distance
 660 between the observer and the lens, and D_{ls} is the orbital separation that we want
 661 to constrain. β is further constrained by

$$\beta \gtrsim \omega \Delta t, \quad (19)$$

662 where ω is the orbital angular velocity of the lens, defined as

$$\omega = \sqrt{\frac{GM_{lens}^3}{D_{ls}^3(M_s + M_{lens})^2}}, \quad (20)$$

663 and Δt is the duration of time in which the pulsar is magnified enough to be
 664 detected above the noise floor.

665 We use Eqs. 16, 17, and 19 to constrain the properties of the binary system and
 666 plot the parameter space shown in Extended Data Figure 6. The orbital inclination

of the lensing system would need to be aligned to the line of sight within 10^{-17} – 10^{-18} arcseconds, depending on the lens mass.

8 Model of merging compact objects

In this section, we expand the model of merging neutron stars described in the main text. One possible interaction of merging neutron stars to produce periodic FRBs is through a unipolar inductor process where the companion orbiting through the magnetic field acts as a conductor driving a current loop. The latter accelerates electrons and positrons to emit curvature radiation^{37–40} in orbital frequencies ranging from few Hz to kHz, corresponding to orbital separations of 10–1000 km in the binary neutron star case. Another proposed mechanism to extract energy is through the magnetic braking and spin-orbital synchronization of merging binary neutron stars.^{41,42}

The loss of angular momentum and energy through gravitational wave radiation causes the compact object binary orbits to decay with a predictable relation between the orbital angular frequency ω and time t . We consider the equation⁶⁰ for the instantaneous orbital angular frequency derivative (with $c=G=1$)

$$\dot{\omega} = \frac{96}{5} \eta m^{5/3} \omega^{11/3} \left[1 - \left(\frac{743}{336} + \frac{11}{4} \eta \right) (m\omega)^{2/3} + 4\pi m\omega + \left(\frac{34103}{18144} + \frac{13661}{2016} \eta + \frac{59}{18} \eta^2 \right) (m\omega)^{4/3} \right]. \quad (21)$$

Here, $m = m_1 + m_2$ and $\eta = m_1 m_2 / m^2$ are the total mass and reduced mass, respectively, of two components of mass m_1 and m_2 . We have assumed that spin-orbit and spin-spin coupling are negligible. For a given set of trial masses,

686 (m_1, m_2) , we numerically integrated the above differential equation twice to cal-
 687 culate the orbital phase ϕ , i.e. we go from $\dot{\omega}(\omega, t) \rightarrow \omega(t) \rightarrow \phi(t)$. The initial
 688 orbital period was chosen to be larger than the periods measured for these FRBs
 689 and the system was evolved till $\omega = 2\pi \times 10^6 \text{ rad s}^{-1}$, very close to the final
 690 merger. We numerically inverted $\phi(t)$ to get $t(\phi)$, the time of passage of the com-
 691 ponents through a specific orbital phase. We use this to fit the ToAs through the
 692 same procedure described in Section 5. We modified Equation 4 as

$$t_i = t(2\pi n_i + \phi_0) + r_i, \quad (22)$$

693 where ϕ_0 is an arbitrary initial phase and the integer-valued n_i vector is defined
 694 in Equation 3. We fixed one of the components to be a neutron star with $m_1 =$
 695 $1.4 M_\odot$ and then searched the parameter space of (m_2, ϕ_0, n_i) to minimize the
 696 root-mean-square of the residuals r_i . We find that the ToAs for FRB 20191221A
 697 and FRB 20210213A are well-fit by this model for a broad range of mass m_2
 698 $(0.1 - 6 M_\odot$ and $1.3 - 6 M_\odot$, respectively) and the same allowed space of “gap-
 699 vectors” n_i as the previous fits. The putative separation of the neutron stars from
 700 their companions for these orbital fits would be 10^3 km and 10^2 km , respectively.

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827 **Extended Data**

Component	20191221A	20210206A	20210213A
$j = 1$	0_{-7}^{+5}	0.00(1)	0.00(3)
$j = 2$	430_{-9}^{+8}	2.221(5)	10.53(8)
$j = 3$	652_{-4}^{+1}	4.974(6)	21.70(3)
$j = 4$	1086.2_{-8}^{+7}	8.358(8)	32.60(2)
$j = 5$	1520_{-2}^{+1}	13.580(9)	44.4(1)
$j = 6$	1736(1)	...	52.48_{-5}^{+4}
$j = 7$	1952_{-2}^{+1}	...	...
$j = 8$	2171(2)	...	...
$j = 9$	2604_{-3}^{+2}	...	...

Extended Data Table 1: **List of ToAs for each event.** ToA of each component forming the three FRBs are reported in milliseconds relative to the first peak. 1- σ uncertainties on the last digit are reported in parenthesis or as sub- and superscripts when they differ.

FRB	N_{ToAs}	N_{gaps}	N_{trials}	$p\text{-value}_{\hat{S}}$	$\sigma_{\hat{S}}$	P (ms)	Z_1^2	$p\text{-value}_{Z_1^2}$	$\sigma_{Z_1^2}$
20191221A	9	3	1365	6.7×10^{-11}	6.5	217.3	18.0	5.0×10^{-10}	6.22
20210206A	5	0	6	0.195	1.3	2.8	6.9	0.9998	0.0002
20210213A	6	1	15	0.019	2.4	10.8	9.7	0.57	0.58

Extended Data Table 2: **Statistical significance of the FRB periodicities.** For each FRB, we report the number of ToAs measured from the profile, the number of gaps and trials considered in the $\hat{S}$ -periodicity analysis, and the resulting probability and significance. The values in the last four columns are derived using the Rayleigh (Z_1^2) test and show the period obtained in the analysis, the resulting value of the test, and the false alarm probability and significance of the periodicities.

Extended Data Figure 1: **Smoothed profile of FRB 20191221A.** The observed profile (gray) is plotted at full resolution (0.98304 ms) and smoothed by using the Savitsky-Golay filter with a polynomial order of 6 and window ~ 300 ms (red). Shaded in blue is the maximum window size we consider, which is 600 ms.

Extended Data Figure 2: χ_{red}^2 **as a function of the number of components fitted for the profile of FRB 20191221A.** The vertical line highlights the chosen number of components, while the horizontal line is placed at the χ_{red}^2 value for 9 components. Error bars are estimated using Eq. 2.

Extended Data Figure 3: **ToAs t_j of the components of FRB 20191221A as a function of their measured cycle n_j .** The cycle is defined in Eq. (3). The periodicity appears clearly as the points fall nearly on a straight line instead of being randomly distributed.

Extended Data Figure 4: **Distribution of maximum Z_1^2 values from $\mathcal{N}_{\text{sim}} = 10^{10}$ Monte Carlo simulations using the measured ToAs from FRB 20191221A.** A Z_1^2 value of 17.96, obtained from the measured ToAs listed in Extended Data Table 1, is indicated by the dashed red line.

Extended Data Figure 5: **RM detection from FRB 20210206A.** Panel a): Measured Stokes Q, U, normalised by the total linear polarization ($P = \sqrt{Q^2 + U^2}$), and polarization angle ψ as a function of frequency with corresponding model fits. Frequency channels with significant polarized signal are highlighted through a greyscale that saturates at higher S/N. Panel b): RM-synthesis displaying polarised intensity as a function of RM. The inset plot highlights the unambiguous RM detection near $+193 \text{ rad m}^{-2}$.

Extended Data Figure 6: **Parameter space allowed (brighter colors) and excluded (shaded regions) to produce the FRBs here reported for a binary system located at 1 Gpc, containing a $1 M_{\odot}$ pulsar emitting 1 Jy pulses.** The minimum alignment angle (color-coded), companion mass and separation of the binary system are reported. Transit times and masses unable to explain the observed pulse durations are used to draw the shaded regions in the plot.