Peer Review File

Manuscript Title: Sub-second periodicity in a fast radio burst

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

General comments

Separate components have been already reported for a few (one-off and repeating) FRBs, both from CHIME and other radiotelescopes. Still, so far, searches for (short) periodicities and quasi-periodic oscillations have been negative, independently of the S/N of the FRB.

This work shows, for the very first time, that at least for one of the three FRBs presented (FRB 20191221A) a sub-second periodicity is detected in a 3-s pulse profile at a very high statistical significance. It is definitely unfortunate that FRB 20191221A has no baseband / polarimetric data, but one cannot ask to have everything. Hints of periodicity for the other two events remain quite interesting, and all together the three events point toward a new (or sub-) group of FRBs.
A new detection with the presence of (the same) periodicity would represent a final proof that at least a fraction of the FRBs is produced in the magnetosphere close to the neutron star. On the other hand, the lack of (re-)detection would challenge this “pulsar-like” emission interpretation and possibly favour the binary neutron stars merging scenario. Other FRB emission models must account for a possible presence of periodicity, too.

What can be learned by the presented result is that the (short) periodic FRBs are likely rare and possibly constitute a distinct class. Apparently, only something like 1 over 1000 has this property. No periodicity is detected in the hundred bursts collected from the very well-studied repeaters FRB 121102 (e.g. Li et al. 2021 - to note the waiting time peak at 3.4 ms, which deserves a deeper investigation in my opinion; Aggarwal et al. 2021 - however a lower limit cut of 50 ms was adopted) and FRB 180916 (Nimmo et al. 2021).

- Are such periodicities “really” so rare to justify a ~ 1/1000 cases detection or we could have missed other events for low statistics, not appropriate data analysis, else? I think the authors can add a comment about this.
- Where do the events properties place them in the overall picture of the FRB catalogue? They seem to fit the proposed “class 3” of the four proposed in Pleunis et al. 2021, so representing about 5% of the population.

With the discovery of new and closer repeaters (rFRBs) and the possibility to observe them with the most sensitive telescopes and with full polarimetric capabilities, it is becoming more and more clear that a large fraction of them can produce extremely short duration “distinct” bursts of emission (see e.g. the multiple components in rFRB 20200120E, Majid et al. 2021, Nimmo et al. 2021). The time duration of the shots is an intrinsic property of the emission mechanism. Detection and measurement of the duration is limited both by the instrumental sensitivity / time resolution (>~ 10 ns) and temporal broadening in the ionised medium along the line of sight. This and the lack of a unique physical description allow us only to put upper limits to the size of the emitting region (excluding likely relevant relativistic effects). Within a statistical framework, what is naturally expected is that, in the absence of a modulation, a range of random time lags must be present (shot-noise) in the multi-component bursts and, eventually, even what appear to be single pulses are in fact the convolution of several shorter shots. To note also that in the case of “wide” events, the number of components is highly dependent on the “optimal” DM used and is also affected by the way the characteristic sub-burst drifts in frequency are treated in the analysis.

- Even though the periodic nature of FRB 20191221A components is clearly visible by eye and the statistical confidence is very high (the detailed work reported in the Methods section is very convincing in this respect), I must say that it is always hard (or impossible) for an external reviewer to verify that the authors considered “all” the possible biases at play. Clearly the authors put a big effort to assess the reality of the periodicity on a small number of pulses (9) covering a time span of 3-s and obtained from a total of about 3000 samples. In fact, in addition to data simulations and the use of classical search techniques, they also introduce the “S” statistic to assess the significance of the periodicity. This seems motivated by the “apparent” gaps present between some consecutive components in FRB 20191221A. However, it does not come out clearly what are the advantages over the Rayleigh periodicity analysis (or other well-established methods), at least for this FRB. It is not mandatory, but I suggest to add, for example, an additional comparative test case on real data. I can think of PSRs with strongly scintillating single pulses. But other data would work too (another multi-component FRB with high time resolution?).

Finally, I assume that follow-up observations are ongoing.

Minor issues / fixes:

- Is the Lyutikov (2021) reconnection-driven free electron laser model capable to reproduce the observed data? Probably it is worth mentioning it.

- rFRB 20200120E: I suggest to cite (and comment) also Nimmo et al. 2021, arXiv:2105.11446

- Page 11, row 214-219: For the sake of clarity, I would explain how the expected P_dot is obtained (the Omega_dot reported in the Methods is not of immediate interpretation) and which ranges are considered acceptable for the three FRBs.

- Page 5, row 78-79: “with some sources having a large number of components”: the statement can be better quantified. For example, in Catalogue 1 I count 22, 8, 3, 1 for sub_num > 1, 2, 3, 4 respectively.

- Page 9, row 163: Centre => Center (for consistency)

- Page 14, row 288: Reference #31 is missing the Journal name

- Equation 5 in Methods: division line should not encompass the summation symbol

- Equation 7 in Methods: make clear the formalism adopted to define N_trials within the parentheses ()

- Fig. 4: “FRB 20210213A” => “FRB 20210206A”

- Extended Data Fig. 5, Panel a: please comment the “double” peak at about 625 MHz in the model fit of the Stokes Q, U and polarization angle.

- Extended Data Fig. 6: please use hatched regions or lighter colours for the three shaded regions. It looks a waste of ink as it is.

Referee #2 (Remarks to the Author):

Summary of the key results:

The CHIME/FRB system is the dominant FRB detector, and has delivered a catalogue of FRBs (dating from 2018 to the middle of 2019) comprising over 600 events.

This manuscript presents the detection of three bursts found since then. All three bursts at least 5 distinct, separated components, with the number of components larger than any previously reported FRB. One of the bursts (FRB 20191221A) is a series of wide scatter-broadened bursts that span 3 seconds, making it one of the most unusual bursts detected to date. In an analysis of the periodicity of the bursts, the manuscript asserts the pulses occur with a period of approximately 217 ms and a statistical significance of 6.5 sigma. The two other bursts (20210206A, 20210213A) showed 5-6 components over tens of millisecond duration. There is only very marginal evidence for periodicity in these bursts. However, for these two bursts voltages were downloaded, which allowed for the more detailed analysis of the burst properties, showing one to be highly linearly polarized with a determined rotation measure. The other burst was not polarized. The presence of short duration periodicity can provide important constraints on FRB emission mechanisms.

The paper concludes by speculating on how the implications of the apparent periodicity for burst emission mechanisms. Given the sub-second periodicity of the emission of 20191221A, the manuscript asserts that the likely source of emission is in a neutron star magnetosphere one of two previously favoured origins for FRB emission. The manuscript also considers two less credible scenarios for burst emission: a lensed “garden variety” pulsar, or emission from a binary neutron star close to merger.
The observation of the first burst is interesting but the analysis and interpretation need to be

strengthened for the result to be considered for publication in Nature.
Originality and significance: if not novel, please include reference:

The observation of 20191221A is unique amongst FRBs reported to date. Never before has burst emission been observed over such a such a long time (possibly because FRB searches are usually blind to such duration events). There is evidence that the emission is periodic, but further statistical tests, discussed below, would strengthen this assertion.

The other two bursts are less unique. Multiple component FRBs have been observed by other FRB experiments capable of capturing baseband data. Cho et al. (2020, ApJL, 2020, 891, 38) shows a high time resolution analysis of the ASKAP FRB 18112, which shows four regularly (but not periodically) spaced components with polarisation position angle of the components vary between bursts and in the brightest component show a variation across the burst. Farah et al. (2019, MNRAS, 488, 2989) also shows examples of mutli-component bursts in a frequency band similar to CHIME. Polarisation position angle swings have been observed in other fast radio burst sources, such as that observed in FRB180301 (Luo et al, 2020, Nature, 586,693).

Data & methodology: validity of approach, quality of data, quality of presentation

The manuscript would be stronger if it commented on the search completeness to 3-second duration FRBs. The burst train is a series of bright, wide bursts. FRB searches have typically focused on millisecond duration emission. For many radio telescopes it is challenging to search for signals of such length because baseline variations. Are there missing events between the 10-50 ms pulse trains of 20210206A and 20210213A?

There is only marginal evidence for variation in polarization position angle in figure 4. The manuscript should state the reference frequency that the polarisation position angle is referred to. It is possible that the differences in PA between the components could be due to the different effective frequencies of the burst components. The interpretation of PA variation is also complicated by the scatter broadening of the pulses which can flatten the polarisation position angle.

Appropriate use of statistics and treatment of uncertainties:

The manuscript attempts to test the hypothesis that the bursts are periodic. They do so largely through simulations in which bursts arrival times are random. However, it is possible that the hypothesis being tested is potentially incorrect. The manuscript notes that pulsar and especially magnetars are observed have quasiperiodic emission withing single pulses. A stronger statistical test would be to compare a purely periodic bursts with quasiperiodic. This would likely result in a useful measurement of the quality factor of the periodicity.

Given the non-Gaussian nature of the statistics it would be more appropriate to report p-values for the significances of the periodicity rather than sigma.

Conclusions: robustness, validity, reliability:

The manuscript argues that the evidence for periodicity indicates that a likely neutron star magnetospheric origin for the FRB emission. The manuscript would be improved if the manuscript considered whether propagation in an intervening plasma could cause variations on the few hundred millisecond observed.

Suggested improvements: experiments, data for possible revision:

It's unclear how representative the three bursts here are of the general FRB population. The collaboration has published a catalogue of 600 FRBs. Further description of the outlier nature of the bursts would strengthen the paper. Do any of the bursts in the 2018-2019.5 catalogue show 5 or more components?

Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions

The final sentence of the abstract is unsupported by the main text or the supplementary material.

Other suggestions:

The manuscript should use refer to "dynamic spectra" rather than "waterfall plots", as the former is widely used outside of pulsar/FRB astronomy.

Line 17: the manuscript should be clearer on what they mean by "origin" of fast radio bursts. There is strong evidence that for a subset of fast radio bursts we know where they "originate".

Line 61: The paper would be improved if it explained briefly for the general reader what "scattering" is.

Line 77: Cho et al. (2020) demonstrated the existence of FRBs with a wide range of separations.

Line 81: The manuscript should specify the periodicity in the separation of the components of 20200120A reported elsewhere.

Line 82: The manuscript should provide some explanation for the proposed periodicity in activity of 20121102A and 20180916A.

Line 111: The bursts have remarkable similarity to 181112 presented in Cho et al. (2020).

Line 121: It is very impressive that it is possible to deconvolve pulses with pulse broadening nearly a factor of 100 greater than the intrinsic width. The manuscript should compare the beaming fraction of the emission with magnetars, given the putative periodicity.

Line 139: the manuscript should summarise possible reasons for depolarization in the main text

Line 186: The paragraph would be improved if it led off with pointing out that the model is disfavored.

Line 203: Is the volumetric rate of FRBs with “pulse trains” consistent with merging neutron stars?

Line 318: antennae -> antenna

Line 336: the manuscript should specify where on the sky tied array beams can be formed

Line 439: If emission was assumed to arise at each “period” would it be possible to place a constraint on pulsed emission at the other rotations?

Line 451: Is the variation of the scatter broadening with frequency consistent with propagation through a turbulent plasma?

Line 678: The manuscript should include a sentence on how coherent radio emission is produced by this mechanism.

Line 689: till -> until

Line 700: The paper would be stronger if it stated the approximate lifetime of these systems.

Figure 3: Does the excess flux density at 2800 ms correspond to an expected burst component?

Author Rebuttals to Initial Comments:

Dear Editor,

We thank you for reviewing our manuscript. A detailed answer to single comments is in the following.

Comments from the editor:

- Ensure it complies with our format requirements as set out at https://www.nature.com/nature/for-authors. You will also need to make some editorial changes to your paper so that it is as brief as possible and complies with our Guide to Authors (https://www.nature.com/nature/for-authors).

>>> To the best of our judgement, the manuscript complies with the guidelines before acceptance.

- The referees raise the issue of how previous searches might have missed long bursts, for technical reasons. We feel that a sentence or two addressing this possible bias would be a good idea.

>>> We agree with this point, even though it is something very difficult to characterize with accuracy. We have added to the manuscript that "Since the detection pipeline of CHIME/FRB is not optimized to find bursts longer than 128 ms, it is possible that some events with comparable duration eluded detection. However, FRB 20191221A was identified using the individual peaks in its profile. Therefore, we expect the fraction of missed long-duration events to be small if single peaks can be identified in their pulse profiles. A detailed analysis of the completeness of the CHIME/FRB search pipeline has been presented elsewhere. (The CHIME/FRB Collaboration 2021)."

- From an editorial perspective, the paper is far too long (2200 words at present, vs the target of 1500 words). The discussion of the various possibilities is quite unfocused and inconclusive. We suggest that you shift most of this to the Methods, with a *very* brief summary in the main text. Otherwise, the novelty of the observational result may get lost in the rather hand-wavy discussion.

>>> We agree and we have moved most of the discussion to the Methods, as suggested, while keeping a summary in the main text. We have also shortened the rest of the Main Text and it is now composed

of ~ 1650 words. Moreover, we have moved one of the figures (the polarization profile for one the bursts) to the Extended Data since it was no longer essential to the discussion. This should comply with Nature's requirements for letters.

- This journal strongly supports public availability of data and custom code. Please place the data and code used in your paper into a public data repository, or alternatively, present the data as Supplementary Information. If data and code can only be shared on request, please explain why in your Data Availability Statement, and also in the correspondence with your editor. Please note that for some data types, deposition in a public repository is mandatory - more information on our data deposition policies and available repositories appears below.

>>> Data and codes used in the manuscript preparation will be made available on public repositories after acceptance. Data include signal intensity as a function of frequency and time for the three sources presented. Codes include our tools to study the significance of the periodicity.

- Nature's preferred approach to sharing research data is via public repositories (http://www.nature.com/authors/policies/availability.html#data), but when this is not possible a DAS should include, at a minimum, a statement confirming that all relevant data are available from the authors and/or are included with the manuscript (e.g. as source data or Supplementary Information). The statement must list which data are included (e.g. by figure panels and data types) and mention any restrictions on availability. If a dataset generated or analysed during the study is publicly available and already has a unique Digital Object Identifier (DOI), we strongly encourage authors to include this in the reference list and to cite the dataset in the Methods. Certain statements that previously would be found in the Author Information section (e.g. observing program numbers) should now be included only in the DAS.

>>> We have updated the statements on data and code availability accordingly in the manuscript.

- FIGURE LEGENDS: The main figure legends should be listed sequentially after the references in the main text. Each legend should begin with a **brief, non-technical** title that does not refer to features in the figure, or contain any parenthetical information. (At present, Fig 1, and ED Figs 4 and 6 do not comply with this requirement.) Any error bars in the figures must be defined (for example, s.d., s.e.m.) and the value of n indicated; see https://www.nature.com/nature/for-authors/formatting-guide for further explanation.

>>> We have updated the label of those figures to comply with the guidelines.

- FIGURE FORMATTING: Lettering in all figures (labelling of axes and so on) should be in uniform, sans-serif font, in lower-case type, and large enough to permit substantial reduction for publication (minimum font size 5 pt). Separate parts of a figure are labelled a, b, etc **and referred to that way in the legends (not "left", "right"). Units have a single space between the number and the unit, and follow SI nomenclature or the nomenclature common to a particular field. Thousands are separated by commas (1,000). Unusual units or abbreviations are defined in the legend. Scale bars rather than magnification factors should be used.

>>> We have updated the figures to comply with the guidelines. Namely, we added the panel letters as required in Fig. 2, ED Fig. 5 and 6.

Referee response:

>>> We thank the referees for their time and effort to provide meaningful suggestions that undoubtedly improved the manuscript. A detailed answer is provided in the following to each point raised by the referees.

Referee #1 (Remarks to the Author):

General comments

Separate components have been already reported for a few (one-off and repeating) FRBs, both from CHIME and other radiotelescopes. Still, so far, searches for (short) periodicities and quasi-periodic oscillations have been negative, independently of the S/N of the FRB.

This work shows, for the very first time, that at least for one of the three FRBs presented (FRB 20191221A) a sub-second periodicity is detected in a 3-s pulse profile at a very high statistical significance. It is definitely unfortunate that FRB 20191221A has no baseband / polarimetric data, but one cannot ask to have everything. Hints of periodicity for the other two events remain quite interesting, and all together the three events point toward a new (or sub-) group of FRBs.

A new detection with the presence of (the same) periodicity would represent a final proof that at least a fraction of the FRBs is produced in the magnetosphere close to the neutron star. On the other hand, the lack of (re-)detection would challenge this “pulsar-like” emission interpretation and possibly favour the binary neutron stars merging scenario. Other FRB emission models must account for a possible presence of periodicity, too.

- What can be learned by the presented result is that the (short) periodic FRBs are likely rare and possibly constitute a distinct class. Apparently, only something like 1 over 1000 has this property.

>>> We have made this more explicit and added a caveat in the following sentence "It is unclear whether FRBs with periodic components may represent a separate and rare class or whether a larger number of FRBs would show periodic behaviours if enough components would be detected."

No periodicity is detected in the hundred bursts collected from the very well-studied repeaters FRB 121102 (e.g. Li et al. 2021 - to note the waiting time peak at 3.4 ms, which deserves a deeper investigation in my opinion; Aggarwal et al. 2021 - however a lower limit cut of 50 ms was adopted) and FRB 180916 (Nimmo et al. 2021).

- Are such periodicities “really” so rare to justify a ~ 1/1000 cases detection or we could have missed other events for low statistics, not appropriate data analysis, else? I think the authors can add a comment about this.

>>> We have added that "Since the detection pipeline of CHIME/FRB is not optimized to find bursts longer than 128 ms, it is possible that some events with comparable duration eluded detection. However, FRB 20191221A was identified using the individual peaks in its profile. Therefore, we expect the fraction of missed long-duration events to be small if single peaks can be identified in their pulse profiles. A detailed analysis of the completeness of the CHIME/FRB search pipeline has been presented elsewhere. (The CHIME/FRB Collaboration 2021)."

- Where do the events properties place them in the overall picture of the FRB catalogue? They seem to fit the proposed “class 3” of the four proposed in Pleunis et al. 2021, so representing about 5% of the population.

>>> We have added that "similar to class 3 FRBs presented by CHIME/FRB (Pleunis et al. 2021), which represent ~ 5\% of the population."

With the discovery of new and closer repeaters (rFRBs) and the possibility to observe them with the most sensitive telescopes and with full polarimetric capabilities, it is becoming more and more clear that a large fraction of them can produce extremely short duration “distinct” bursts of emission (see e.g. the multiple components in rFRB 20200120E, Majid et al. 2021, Nimmo et al. 2021). The time duration of the shots is an intrinsic property of the emission mechanism. Detection and measurement of the duration is limited both by the instrumental sensitivity / time resolution (>~ 10 ns) and temporal broadening in the ionised medium along the line of sight. This and the lack of a unique physical description allow us only to put upper limits to the size of the emitting region (excluding likely relevant relativistic effects). Within a statistical framework, what is naturally expected is that, in the absence of a modulation, a range of random time lags must be present (shot-noise) in the multi-component bursts and, eventually, even what appear to be single pulses are in fact the convolution of several shorter shots. To note also that in the case of “wide” events, the number of components is highly dependent on the “optimal” DM used and is also affected by the way the characteristic sub-burst drifts in frequency are treated in the analysis.

- Even though the periodic nature of FRB 20191221A components is clearly visible by eye and the statistical confidence is very high (the detailed work reported in the Methods section is very convincing in this respect), I must say that it is always hard (or impossible) for an external reviewer to verify that the authors considered “all” the possible biases at play. Clearly the authors put a big effort to assess the reality of the periodicity on a small number of pulses (9) covering a time span of 3-s and obtained from a total of about 3000 samples. In fact, in addition to data simulations and the use of classical search techniques, they also introduce the “S” statistic to assess the significance of the periodicity. This seems motivated by the “apparent” gaps present between some consecutive components in FRB 20191221A. However, it does not come out clearly what are the advantages over the Rayleigh periodicity analysis (or other well-established methods), at least for this FRB. It is not mandatory, but I suggest to add, for example, an additional comparative test case on real data. I can think of PSRs with strongly scintillating single pulses. But other data would work too (another multi-component FRB with high time resolution?).

>>> We demonstrate in the Methods (section "Significance of the periodicity") that the S statistics we use is near-optimal, a reason to use it instead of more classic methods. However, we also provide the correspondent values of the Rayleigh statistics in Extended Data Table 2 for interested readers. We do not believe that applying the statistics on pulsar timeseries would provide additional information since it would demonstrate that the two statistics are able to recover periodic signals, whereas in this context, we need to verify that spurious signals would not give false periodicities. Therefore, we believe that the current simulations address the problem.

- Finally, I assume that follow-up observations are ongoing.

>>> We have added that "CHIME/FRB continues to monitor the sky location of these FRBs daily for possible additional bursts."

Minor issues / fixes:

- Is the Lyutikov (2021) reconnection-driven free electron laser model capable to reproduce the observed data? Probably it is worth mentioning it.

>>> We do not think this is essential for the current paper after the Editor asked us to reduce the length of the discussion in the Main text. However, the paper from Lyutikov (2021) states that "FRBs might last ~ 10E-2 of the period". The period we measure for FRB 20191221A is 216.8 ms, while the average width of single components is ~ 4 ms, a factor of 2 larger than predicted but well within the uncertainties of the model and the measurements. If the periodicities found for the other two sources is true, we find a factor of ~ 2E-2 and 4E-2, respectively, between their average widths and periodicities, also broadly in agreement with the model.

- rFRB 20200120E: I suggest to cite (and comment) also Nimmo et al. 2021, arXiv:2105.11446

>>> We have added that "hints of possible shorter periodic separations of ~ 2.3 us and ~ 0.3 us in the components of other FRBs have recently been presented (Majid et al. 2021; Nimmo et al. 2021)."

- Page 11, row 214-219: For the sake of clarity, I would explain how the expected P_dot is obtained (the Omega_dot reported in the Methods is not of immediate interpretation) and which ranges are considered acceptable for the three FRBs.

>>> We have reduced this section and moved it to the Methods as suggested by the Editor. However, we have added the relation between P_dot and Omega_dot

- Page 5, row 78-79: “with some sources having a large number of components”: the statement can be better quantified. For example, in Catalogue 1 I count 22, 8, 3, 1 for sub_num > 1, 2, 3, 4 respectively.

>>> We have modified the sentence to "these FRBs demonstrate the existence of a broad distribution in the number of components in burst profiles, with some sources showing possible periodic separations." Therefore, we think this comment is no longer relevant.

- Page 9, row 163: Centre => Center (for consistency)

>>> We have edited all the instances to be consistent with the British spelling.

- Page 14, row 288: Reference #31 is missing the Journal name

>>> Fixed

- Equation 5 in Methods: division line should not encompass the summation symbol

>>> Fixed

- Equation 7 in Methods: make clear the formalism adopted to define N_trials within the parentheses ()

>>> We have changed the bracket notation of the Binomial coefficient with the explicit formula.

- Fig. 4: “FRB 20210213A” => “FRB 20210206A”

>>> Fixed

- Extended Data Fig. 5, Panel a: please comment the “double” peak at about 625 MHz in the model fit of the Stokes Q, U and polarization angle.

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- Extended Data Fig. 6: please use hatched regions or lighter colours for the three shaded regions. It looks a waste of ink as it is.

>>> Fixed

Referee #2 (Remarks to the Author):

Summary of the key results:

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The paper concludes by speculating on how the implications of the apparent periodicity for burst emission mechanisms. Given the sub-second periodicity of the emission of 20191221A, the manuscript asserts that the likely source of emission is in a neutron star magnetosphere one of two previously favoured origins for FRB emission. The manuscript also considers two less credible scenarios for burst emission: a lensed “garden variety” pulsar, or emission from a binary neutron star close to merger.

The observation of the first burst is interesting but the analysis and interpretation need to be strengthened for the result to be considered for publication in Nature.

Originality and significance: if not novel, please include reference:

The observation of 20191221A is unique amongst FRBs reported to date. Never before has burst emission been observed over such a such a long time (possibly because FRB searches are usually blind to such duration events). There is evidence that the emission is periodic, but further statistical tests, discussed below, would strengthen this assertion.

The other two bursts are less unique. Multiple component FRBs have been observed by other FRB experiments capable of capturing baseband data. Cho et al. (2020, ApJL, 2020, 891, 38) shows a high time resolution analysis of the ASKAP FRB 18112, which shows four regularly (but not periodically) spaced components with polarisation position angle of the components vary between bursts and in the brightest component show a variation across the burst. Farah et al. (2019, MNRAS, 488, 2989) also shows examples of mutli-component bursts in a frequency band similar to CHIME. Polarisation position angle swings have been observed in other fast radio burst sources, such as that observed in FRB180301 (Luo et al, 2020, Nature, 586,693).

Data & methodology: validity of approach, quality of data, quality of presentation

- The manuscript would be stronger if it commented on the search completeness to 3-second duration FRBs. The burst train is a series of bright, wide bursts. FRB searches have typically focused on millisecond duration emission. For many radio telescopes it is challenging to search for signals of such length because baseline variations. Are there missing events between the 10-50 ms pulse trains of 20210206A and 20210213A?

>>> We have added that "Since the detection pipeline of CHIME/FRB is not optimized to find bursts longer than 128 ms, it is possible that some events with comparable duration eluded detection. However, FRB 20191221A was identified using the individual peaks in its profile. Therefore, we expect the fraction of missed long-duration events to be small if single peaks can be identified in their pulse profiles. A detailed analysis of the completeness of the CHIME/FRB search pipeline has been presented elsewhere. (The CHIME/FRB Collaboration 2021)."

- There is only marginal evidence for variation in polarization position angle in figure 4.

>>> We do not agree with the referee that the evidence for PA variation in Fig. 4 is marginal. A simple reduced chi-square test with a straight line gives a value of 8, clearly inconsistent with a flat curve.

- The manuscript should state the reference frequency that the polarisation position angle is referred to.

>>> We have added that the PA is "referenced to infinite frequency".

- It is possible that the differences in PA between the components could be due to the different effective frequencies of the burst components.

>>> As visible in Fig. 2, and reported in the text, there is not a large variation in the spectrum of single components of the same FRB.

- The interpretation of PA variation is also complicated by the scatter broadening of the pulses which can flatten the polarisation position angle.

>>> We agree that scattering can flatten the PA curve but it would only strengthen the message of the figure that different components have different PA values, which seems somehow unusual among FRBs (e.g. Michilli et al. 2018)

Appropriate use of statistics and treatment of uncertainties:

- The manuscript attempts to test the hypothesis that the bursts are periodic. They do so largely through simulations in which bursts arrival times are random. However, it is possible that the hypothesis being tested is potentially incorrect. The manuscript notes that pulsar and especially magnetars are observed have quasiperiodic emission withing single pulses. A stronger statistical test would be to compare a purely periodic bursts with quasiperiodic. This would likely result in a useful measurement of the quality factor of the periodicity.

>>> The statistical tests currently in the manuscript aim to distinguish the case of periodicity with respect to random times of arrival, which is the primary message of the paper. The degree of strict periodicity vs quasi-periodicity is challenging to be robustly quantified with only 9 components. However, it can be estimated with a chi-square test of Fig. 2b, which is given in ED Fig. 2 for FRB 20191221A.

- Given the non-Gaussian nature of the statistics it would be more appropriate to report p-values for the significances of the periodicity rather than sigma.

>>> We agree and have edited the text accordingly.

Conclusions: robustness, validity, reliability:

- The manuscript argues that the evidence for periodicity indicates that a likely neutron star magnetospheric origin for the FRB emission. The manuscript would be improved if the manuscript considered whether propagation in an intervening plasma could cause variations on the few hundred millisecond observed.

>>> The suggested scenario appears unrealistic. In fact, a multi-component FRB may be generated by propagation effects in two ways. In the first model, a steady signal could be modulated by intervening plasma with sharp variations in its optical thickness. These variations should either oscillate on a 218-ms timescale or move with respect to the source line-of-sight to create a pattern similar to the observed one. Alternatively, a single-component FRB could be lensed multiple times. To produce a periodic signal, these unlikely scenarios would require even finer-tuned assumptions. We thus do not consider it necessary to discuss this hypothesis in the manuscript.

Suggested improvements: experiments, data for possible revision:

- It’s unclear how representative the three bursts here are of the general FRB population. The collaboration has published a catalogue of 600 FRBs. Further description of the outlier nature of the bursts would strengthen the paper. Do any of the bursts in the 2018-2019.5 catalogue show 5 or more components?

>>> We indicate that "in a small fraction of events detected by CHIME/FRB (< 0.5\%), five or more separate components are visible in the pulse profiles", and that "[nine overlapping components.] No other FRB candidate observed by CHIME/FRB contains a comparable or greater number of sub-components."

Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions

- The final sentence of the abstract is unsupported by the main text or the supplementary material.

>>> We have removed this sentence

Other suggestions:

- The manuscript should use refer to “dynamic spectra” rather than “waterfall plots”, as the former is widely used outside of pulsar/FRB astronomy.

>>> The term "dynamic spectra" has a specific meaning in pulsar studies - i.e. considering only the on-pulse emission while discarding the time spans without signal detected from the source. Here, we prefer the more general "waterfall plot". We included an explanation of the meaning of the term to avoid any ambiguity.

- Line 17: the manuscript should be clearer on what they mean by “origin” of fast radio bursts. There is strong evidence that for a subset of fast radio bursts we know where they “originate”.

>>> The sentence has been reworded to avoid ambiguities. .

- Line 61: The paper would be improved if it explained briefly for the general reader what “scattering” is.

>>> We now indicate that scattering is "a pulse broadening caused by propagation of the radio waves in turbulent plasma".

- Line 77: Cho et al. (2020) demonstrated the existence of FRBs with a wide range of separations.

>>> While Cho et al. (2020) presented one FRB (181112) with 4 components (two of which are very faint), the FRBs shown here are composed of 5 or more separate components.

- Line 81: The manuscript should specify the periodicity in the separation of the components of 20200120A reported elsewhere.

>>> We have added this information. We have edited the sentence to also cite Nimmo et al. 2021 to " Hints of shorter periodic separations of ~2.3 μs and ~0.3 μs in the components of other FRBs have also been recently presented."

- Line 82: The manuscript should provide some explanation for the proposed periodicity in activity of 20121102A and 20180916A.

>>> The current manuscript does not discuss the periodicity in activity of 20121102A and 20180916A and, moreover, we explain in the manuscript that "we do not consider the two phenomena to be related". Therefore, an explanation of the proposed periodicity in activity of 20121102A and 20180916A is outside the scope of the paper.

- Line 111: The bursts have remarkable similarity to 181112 presented in Cho et al. (2020).

>>> We have now put the morphology in the context of the recent CHIME/FRB's catalog v1 by adding that the bursts look "similar to class 3 FRBs presented by CHIME/FRB, which represent ~ 5\% of the population".

- Line 121: It is very impressive that it is possible to deconvolve pulses with pulse broadening nearly a factor of 100 greater than the intrinsic width. The manuscript should compare the beaming fraction of the emission with magnetars, given the putative periodicity.

>>> We have added the sentence "This corresponds to a duty cycle of ~ 1.8%, consistent with galactic radio magnetars and pulsars."

- Line 139: the manuscript should summarise possible reasons for depolarization in the main text

>>> We have shortened the paragraph and indicated that "possible reasons for this are discussed in the Methods" to avoid adding discussions not essential to the scope of the paper.

- Line 186: The paragraph would be improved if it led off with pointing out that the model is disfavored.

>>> We agree with the referee and have added the sentence "one unlikely scenario" at the beginning of the paragraph. We have also moved the full paragraph to the Methods as suggested by the Editor.

- Line 203: Is the volumetric rate of FRBs with “pulse trains” consistent with merging neutron stars?

>>> Since we report only one significant periodic FRB plus two possible candidates, the volumetric rate necessary to explain periodic FRBs is compatible with observations.

- Line 318: antennae -> antenna

>>> The current wording is the right to be used since multiple antennae are summed together.

- Line 336: the manuscript should specify where on the sky tied array beams can be formed

>>> We specified that "thanks to the phase information available in baseband data, synthesized beams can be formed to virtually any position on the sky within the primary field of view of the telescope".

- Line 439: If emission was assumed to arise at each “period” would it be possible to place a constraint on pulsed emission at the other rotations?

>>> This would need assuming that all the individual peaks have the same intensity, which is clearly not the case.

- Line 451: Is the variation of the scatter broadening with frequency consistent with propagation through a turbulent plasma?

>>> Propagation through a turbulent plasma produces a scattering tail in the pulse profile that we modelled with a simple exponential function. The extreme value of the scattering timescale measured for FRB 20191221A indeed points to a turbulent medium, and we have now specified this in the text ("pointing to propagation through a turbulent plasma"). We have not checked the spectral index of the scattering tail since overlapping components prevent a robust estimate. The scattering measured for the other two FRBs is not as exceptional, and we state this explicitly in the text ("The other two FRBs show narrower widths and shorter scattering timescales typical of the FRB population.").

- Line 678: The manuscript should include a sentence on how coherent radio emission is produced by this mechanism.

>>> We have briefly described the possible emission mechanism hypothesized by the cited authors.

- Line 689: till -> until

>>> Fixed

- Line 700: The paper would be stronger if it stated the approximate lifetime of these systems.

>>> The time to merger for these systems has been added as a range since it depends on the companion masses.

- Figure 3: Does the excess flux density at 2800 ms correspond to an expected burst component?

>>> That component is found to be not statistically significant. However, it would correspond to an expected component and, as visible in Extended Data Fig. 2, its inclusion would give an even smaller p-value of ~ 5e-12 (the value is approximated as the number of simulations required to properly quantify it is higher than the current number).

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

I only have some minor comments to the revised version, after which I consider the manuscript acceptable for publication.

- The follow-up observations I mentioned in my report refer “also” (if not only) to facilities “other than CHIME” as this is the canonical (and definitive) way to confirm the detection of unique events like this, “independently”. Of course, assuming it will repeat… We all know about the story of the first detected FRBs at Parkes.

- I still would like to see the S statistic in action in other astrophysical contexts.

Minor fixes:

Page 5: …periodicities does not represent… => do not

Page 21: Figure 3 => Extended Data Figure 3; also please adopt “n_i, t_i” as axis labels in that figure (and in Extended Data Table 1, “i=” or just remove “j=” ?)

Page 24: FRB 20210213A => FRB 20191221A

Page 27: … DM-inferred distance … => Can add the DM-inferred distance also for the other two FRBs

Referee #2 (Remarks to the Author):

The authors have addressed and responded to most of the comments raised in the first round of refereeing. I’m still concerned about the connection between 20191221A and the other two bursts presented in the manuscript. This will only be resolved with a larger sample of bursts.

I am still concerned about the way the authors assess the statistical significance of the periodicity. The authors test against a null hypothesis that the burst arrival times are statistically independent burst to burst. if the bursts arrive quasiperiodically, under the current test, the null hypothesis could presumably be rejected with high significance. This could well be the case for FRBs 202210206A and 20210213A, where the residuals plotted in Figure 1 do not show phase-connected timing expected from a pulsar. The residuals for 20191221A are more convincing. The paper would be much stronger if it put a constraint on the quasiperiodicity of its burst trains. This could then be used by others to test theories in which may predict quasiperiodic arrival times.

The authors should at least acknowledge that their statistical tests would not be able to distinguish between bursts that arrive periodically and those that arrive quasiperiodically.

Other suggestions:

First paragraph: the authors should report a p-value here rather than a significance of 6.5 sigma.

First paragraph: the authors should be quantitative when stating that 202102026A and 20210213A instead of stating the bursts have “some indication” of periodic separations.

Second paragraph main text (Page 6): In less than -> In fewer than

Page 6: “class 3 FRBs” is introduced without context. The CHIME burst morphology classification scheme has not (yet) been widely adopted so some more explanation is needed here.

Last paragraph, page 6: extragalactic -> extra-Galactic (the contribution refers the media outside the Galaxy, not all galaxies)

Methods:

Antennae vs antennas: The authors should consider using the more commonly used “antennas” as the plural for antenna rather than “antennae”.

The y-axis of Extended Figure 3 needs units.

Author Rebuttals to First Revision:

Referees' comments:

- We thank again the referees for a constructive exchange of ideas that has improved the manuscript.

Referee #1 (Remarks to the Author):

I only have some minor comments to the revised version, after which I consider the manuscript acceptable for publication.

- The follow-up observations I mentioned in my report refer “also” (if not only) to facilities “other than CHIME” as this is the canonical (and definitive) way to confirm the detection of unique events like this, “independently”. Of course, assuming it will repeat… We all know about the story of the first detected FRBs at Parkes.

>>> Currently, we are observing the source only with CHIME. We hope that publishing the manuscript will foster interest among the community to use other facilities.

- I still would like to see the S statistic in action in other astrophysical contexts.

>>> We have tested the statistics on pulsar PSR B1919+21 and added the following sentence to the Methods: "As a further test of our pipeline, we applied the $\hat S$ statistic to CHIME observations of the bright pulsar PSR B$1919+21$. If we select three pulses with one gap, periodicity is detected at the $\sim 3\sigma$ level. If we select four pulses with either one or two gaps, periodicity is detected at $>4\sigma$."

Minor fixes:

Page 5: …periodicities does not represent… => do not

>>> Fixed

Page 21: Figure 3 => Extended Data Figure 3; also please adopt “n_i, t_i” as axis labels in that figure (and in Extended Data Table 1, “i=” or just remove “j=” ?)

>>> Fixed

Page 24: FRB 20210213A => FRB 20191221A

>>> Fixed

Page 27: … DM-inferred distance … => Can add the DM-inferred distance also for the other two FRBs

>>> The DM-inferred distance has been added

Referee #2 (Remarks to the Author):

- The authors have addressed and responded to most of the comments raised in the first round of refereeing. I'm still concerned about the connection between 20191221A and the other two bursts presented in the manuscript. This will only be resolved with a larger sample of bursts.

>>> We agree and the importance of the other two FRBs has been significantly reduced in the latest version of the manuscript. Only a mention of these events is now present in the main text highlighting the low significance whereas their analysis and discussion have been moved to the methods.

- I am still concerned about the way the authors assess the statistical significance of the periodicity. The authors test against a null hypothesis that the burst arrival times are statistically independent burst to burst. if the bursts arrive quasiperiodically, under the current test, the null hypothesis could presumably be rejected with high significance. This could well be the case for FRBs 202210206A and 20210213A, where the residuals plotted in Figure 1 do not show phase-connected timing expected from a pulsar. The residuals for 20191221A are more convincing. The paper would be much stronger if it put a constraint on the quasiperiodicity of its burst trains. This could then be used by others to test theories in which may predict quasiperiodic arrival times.

>>> For FRB 20191221A, the manuscript now reports the deviation of the residuals with respect to a straight line expected for a perfect periodicity. Given the value of a reduced chi-squared test of 1.09 with 9 data points, there are no doubts about its periodicity. As mentioned above, the importance given to the two other sources has been diminished and the low significance of their periodicity is well highlighted in the text.

- The authors should at least acknowledge that their statistical tests would not be able to distinguish between bursts that arrive periodically and those that arrive quasiperiodically.

>>> Even the most periodic sources known, pulsars, show some deviations from a strict periodicity, in a few cases as small as our best atomic clocks. This is to say that a perfect periodicity does not exist but there are different levels of deviations from a perfect periodicity or, in other words, different levels of quasi periodicity. Therefore, it is not possible to have a statistical test distinguishing a periodic source from a quasi-periodic source since it is a continuous distribution rather than two separate classes. Often, quasi-periodicity is referred to sources where a peak can be seen in the dynamic spectrum but its significance is low when performing a proper timing analysis. This is extensively discussed in the manuscript for the three FRBs, both in this fashion and in the context of quasi-periodic pulses that are relatively common in the pulsar literature. In summary, FRB 20191221A is close to a strict periodicity, with a reduced chi-squared of 1.09 (now explicitly mentioned in the main text to highlight this). The other two sources are farther from a perfect periodicity and they have been moved to the Methods, with only a quick mention now present in the main text. Whether these two sources are quasi-periodic or have a large jitter, it is impossible to say with the small number of components detected regardless of the test used.

Other suggestions:

- First paragraph: the authors should report a p-value here rather than a significance of 6.5 sigma.

>>> We believe it is important to keep a comparison in terms of sigma for the broader community since this is often used in other fields, such as atomic physics. The relative p-value is already presented in the text and we do not repeat it here for brevity's sake.

- First paragraph: the authors should be quantitative when stating that 202102026A and 20210213A instead of stating the bursts have “some indication” of periodic separations.

>>> We agree and have removed these less significant sources from the abstract altogether.

- Second paragraph main text (Page 6): In less than -> In fewer than

>>> Fixed

- Page 6: “class 3 FRBs” is introduced without context. The CHIME burst morphology classification scheme has not (yet) been widely adopted so some more explanation is needed here.

>>> We have removed the mention to the class 3 FRB and only indicated that a similar morphology is visible in ~ 5% of the bursts.

- Last paragraph, page 6: extragalactic -> extra-Galactic (the contribution refers the media outside the Galaxy, not all galaxies)

>>> We think the current version is correct. In any case, this will be checked by the Nature revision team.

Methods:

- Antennae vs antennas: The authors should consider using the more commonly used “antennas” as the plural for antenna rather than “antennae”.

>>> Fixed

The y-axis of Extended Figure 3 needs units.

>>> Fixed