Peer Review File

Manuscript Title: A repeating fast radio burst source in a globular cluster

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referee #1 (Remarks to the Author):

[redacted]

[redacted]

[redacted]

[redacted]

Summary: This manuscript presents the VLBI localisation of FRB20200120E to a known globular cluster associated with M81. This is itself a stunning finding, given the widely held view that FRB sources are young neutron stars. Constraints are placed on persistent emission from the location of the FRB that are a few orders of magnitude below those previously determined for FRB sources. The distance measurement means that bursts from FRB20200120E bridge the energy gap between Galactic pulsars and the previously known FRB population (including the bright burst observed from the Galactic magnetar SGR1935+2154). The localisation also enables important constraints on the DM and RM of the Milky Way halo.

These results are significant, and are of broad, immediate interest to the astronomy community. I believe that they should be published in Nature. However, there are some issues that need to be addressed in any future revision.

- The localisation (biggest issue)

As presented, the localisation is suspect. I am most concerned by the image-plane fitting to the "fringe envelope" to derive the localisation. Given the distribution of EVN stations that were used, I do not think that the envelope corresponds to any short baseline. I also struggle to see how, with any reasonable correlation parameters, the envelope can correspond to the field of view defined by smearing. I also reached this conclusion based on the offset between the final position and the correlation phase centre given in Section 2.1. Is it perhaps caused by the visibility weighting scheme, or the application of the gridding kernel? For bursts B3 and B4, which are the primary contributors to the localisation, I identify the FWHM of the envelope as approximately 0.5''. This is a few-ns delay on a typical 1000-km baseline. It is very surprising that this is the best accuracy to which the relative burst-signal arrival times at different stations can be measured. It is also very surprising that for a single burst the envelope is highly one-dimensional. This makes me suspect that the envelope is caused by a systematic issue, perhaps with one baseline, and that it does not represent the true burst position.

I re-read the previous Marcote et al. papers on FRB localisations with the EVN, and found no mentions of fringe envelopes. In all those cases, the burst images could be deconvolved, which is an important demonstration that the calibration has been successful and that systematics have been mitigated.

To address this issue, the authors should demonstrate the validity of this non-standard localisation technique on known sources, like pulsars or perhaps other FRB data. Care should be taken to match the array configurations, and signal to noise ratios. Substantial further detail is required on the parameters of the correlation, and the sensitivities of individual antennas. The authors should present a conceptual explanation of the origin of the fringe envelope. Jackknife tests should be done to ensure that one or a few bad antennas are not dominating the localisation. Visibility-domain modeling of the data should be used to support the conclusions reached from the images.

- Analysis of the globular cluster properties

The authors attempt to model the physical properties of the globular cluster using stellar population synthesis with Prospector. However, no discussion is made of previous results on this cluster (e.g., https://ui.adsabs.harvard.edu/abs/2007PASP..119.1085M/abstract and references therein), and it is not clear how this analysis is relevant to the discussion in the paper. As the authors note, the low metallicity may be interesting in the context of young pulsars found in Milky Way globular clusters, and more could be made of this. If the authors wish to persist with the Prospector analysis, I request that they show either a corner plot or a plot of the chains. There is a likely error in R_eff in Table 3.

- Unnecessary content

Much of the discussion in Section 4 can be significantly refined. Rather than presenting a wider range of speculations on the source, I request that any discussion be focused on exactly which source models are disfavoured for FRB20200120E based on the association with a globular cluster. The discussion on ULXs, for example, could be dealt with in one sentence. The discussion and figure on Faraday rotation does not add anything useful and can be excluded.

- Implications for other FRB sources (minor point)

Although FRB20200120E is discussed in the context of other FRB sources, as [redacted] demonstrate (their Figure 2) the duration-averaged bursts are around an order of magnitude less luminous than the brightest burst from SGR1935+2154. This is at the level where questions may be raised about whether this source is capable of producing bursts with similar energies to the more distant FRB population. Some discussion of this, or perhaps a demonstration with more data if present, would help the community in assessing the broader applicability of these findings.

Referee #2 (Remarks to the Author):

The manuscript "A repeating fast radio burst source in a globular cluster" by Kirsten et al. presents the localization of the repeating FRB 20200120E to a globular cluster in M81, making it both the nearest localized FRB and challenging models in which FRB systems are formed in a young stellar population. The paper presents compelling results and a reasonable level of analysis. It needs to be significantly reformatted and shortened into a Nature Letter style, but I leave this to the editor. I recommend the paper for publication in Nature, but I do have a few questions that should be addressed.

[1] How do the authors know this is an FRB and not a RRAT?

[2] Abstract: The authors state that they "propose that FRB 20200120E is a young, highly magnetised neutron star, formed via either accretion-induced collapse of a white dwarf or via merger of compact stars in a binary system." This scenario has been studied in detail by Margalit, Berger, & Metzger 2019, ApJ, 886, 110 and should be properly cited.

[3] Figure 4: the caption ends with "It is obvious that [PR95] 30244 is resolved". However, this is not obvious at all from the profiles shown which are only marginally broader than the PSF of stellar sources in the field. This should be handled more carefully here and in the text.

[4] Figure 6: Prospector provides uncertainty regions for the fits - these should be shown.

[5] Line 435: "Subtracting the FWHMs of the isolated stars in quadrature..." I'm not convinced that this is the correct approach to measuring the size of the source. This leads to an inferred source size that is smaller than the angular resolution (seeing) of the image.

Referee #3 (Remarks to the Author):

The authors present the results of multi-wavelength observations of the recently detected Fast Radio Burst, FRB20200120E, which was originally observed to have low DM and was loosely localised near to the M81 galaxy. Observations include VLBI with dishes from the EVN, VLA data, and well as archival optical and X-ray data. Four bursts were detected with in VLBI data, which allowed for precise localisation of the FRB, sufficient to associate it a globular cluster ([PR95] 30244) known to be associated with M81. Based on the association of FRB20200120E with [PR95] 30244, and that of [PR95] 30244 with M81, the authors show that FRB20200120E is the closest know extragalactic FRB. This is a significant result, with a number of implications for FRB formation models. By way of modelling and using SDSS spectra the authors conclude that [PR95] 30244 is an old metal poor globular cluster, consistent with previous results. From this they go on to argue that the standard core collapse supernovae formation channel for magnetars, which are often claimed as a likely FRB progenitor, is hard to reconcile with such an old system, since the typical lifetimes of a core collapse supernova progenitor is far less than that estimated for [PR95] 30244. The association of the FRB with the globular cluster is well reasoned, and with a low probability of chance overlap, appears to be robust.

Together with radio continuum and X-ray data, the authors place upper limits source luminosities, which will help to constrain FRB progenitor models. Numerous data analysis tools and methods were used in this work. Their descriptions are sufficient to inform the reader of their purpose, though their inner working may be opaque to those without experience with such packages. The wording of the abstract, introduction and conclusion is clear, and appropriate.

Minor comments :
Line 81: Typo. Presumable —> Presumably
Line 322: Wording is unclear. Possibly try “Except for B1, we found all burst in the data recorded by PSRIX…”
Line 614: Word missing. There no —> There are no

Aside from those minor points, I am satisfied with the quality of this paper and recommend it for publication.

Author Rebuttals to Initial Comments:

Referee #1

- The localisation (biggest issue)

[1] As presented, the localisation is suspect. I am most concerned by the image-plane fitting to the "fringe envelope" to derive the localisation. Given the distribution of EVN stations that were used, I do not think that the envelope corresponds to any short baseline. I also struggle to see how, with any reasonable correlation parameters, the envelope can correspond to the field of view defined by smearing. I also reached this conclusion based on the offset between the final position and the correlation phase centre given in Section 2.1. Is it perhaps caused by the visibility weighting scheme, or the application of the gridding kernel? For bursts B3 and B4, which are the primary contributors to the localisation, I identify the FWHM of the envelope as approximately 0.5''. This is a few-ns delay on a typical 1000-km baseline. It is very surprising that this is the best accuracy to which the relative burst-signal arrival times at different stations can be measured. It is also very surprising that for a single burst the envelope is highly one-dimensional. This makes me suspect that the envelope is caused by a systematic issue, perhaps with one baseline, and that it does not represent the true burst position.

Response

The localization presented in this revised manuscript has significantly improved. The derived position is consistent with the previous one, but we have significantly reduced the uncertainties in such position. We noticed that the data from one estation (Urumqi) were recorded with linearly polarized products (as recorded locally at the station). The conversion to circular polarization done after correlation was not successful, ending up in (time-dependent) amplitude errors, among other effects. After discarding the data from this station and using an improved model for the phase calibrator source, the resulting dirty images reflected a pattern equivalent to the expected one for a point-like source (i.e. the dirty beam). The ambiguity raised in the first version of this manuscript is thus gone. The obtained position for the bursts is robust against all tests we have performed during the analysis of the data: different robust weighting, (uv) tapering, and/or flagging specific antennas. We have confirmed that the image is not dominated by any particular antenna as any subset of the array reproduces a consistent position for FRB 20200120E.

To address the referee's comment, we note that in this type of observations the main cause of issues arises from phase and/or amplitude errors, that either cannot be fully corrected during calibration and/or they are generated from the phase-referencing technique. The (time/frequency) smearing is not significant here (<10%) for the measured offsets with respect to the correlated position.

[2] I re-read the previous Marcote et al. papers on FRB localisations with the EVN, and found no mentions of fringe envelopes. In all those cases, the burst images could be deconvolved, which is an important demonstration that the calibration has been successful and that systematics have been mitigated.

Response

The referee is right on the fact that the fringe pattern was not present in the localization of FRB 20180916B (Marcote et al. 2020), where a better (uv) coverage was obtained. However, a similar pattern was actually present in the first localization, FRB 20121102A (Marcote et al. 2017), see Fig. 3 (bottom left). For the faint bursts we had ambiguities between a few fringes, which ultimately ended up in the scatter on the positions reported in Fig. 1. In that case, however, we had a very sensitive baseline formed by the Effelsberg and Arecibo telescopes (which also was the longest baseline in the array). And this was the main reason why the fringe envelope was minimized to tens of milliarcseconds. In the case of the current manuscript, the sensitive baselines are much shorter and thus the envelope covers a broader scale. In any case, as quoted above, the latest results produced a better dirty image.
We also note that the bursts from FRB 20200120E were concentrated at the bottom part of the observed band (see Fig. 1). However, as it can be seen in Table 3, most of the telescopes observed the upper half band. This resulted in the fact that most of the burst emission was only

recorded by only a few telescopes. Resulting in a more sparse (uv) coverage that resulted in the stronger fringe pattern.

[3] To address this issue, the authors should demonstrate the validity of this non-standard localisation technique on known sources, like pulsars or perhaps other FRB data. Care should be taken to match the array configurations, and signal to noise ratios. Substantial further detail is required on the parameters of the correlation, and the sensitivities of individual antennas. The authors should present a conceptual explanation of the origin of the fringe envelope. Jackknife tests should be done to ensure that one or a few bad antennas are not dominating the localisation. Visibility-domain modeling of the data should be used to support the conclusions reached from the images.

Response
The validity of this technique has been demonstrated in Marcote et al (2017, ApJL, 834, L8), where we applied it to single pulses from PSR B0525+21, which already had a known position. This analysis proved that we recover the true position for single bursts, and the precision scales as the fluence and square root of the temporal burst width.
Additionally to that, we have performed a more detailed study on the same pulsar, plus two RRATs (Huang et al. in prep). The 18 bursts detected from FRB 20201124A (Marcote et al. 2021, ATel #14603; paper in prep) are also being used to perform the same statistical studies with equivalent results to the ones presented here. The findings of this study support the localizations performed in Marcote et al. (2017, 2020), and this manuscript, under different observing conditions and number of antennas. We have improved the description of this, and updated to the latest results.

- Analysis of the globular cluster properties

The authors attempt to model the physical properties of the globular cluster using stellar population synthesis with Prospector. However, no discussion is made of previous results on this cluster (e.g., https://ui.adsabs.harvard.edu/abs/2007PASP..119.1085M/abstract<https://ui.adsabs.harvard.edu/abs/2007PASP..119.1085M/abstract> and references therein), and it is not clear how this analysis is relevant to the discussion in the paper. As the authors note, the low metallicity may be interesting in the context of young pulsars found in Milky Way globular clusters, and more could be made of this. If the authors wish to persist with the Prospector analysis, I request that they show either a corner plot or a plot of the chains. There is a likely error in R_eff in Table 3.

Response
We model the physical properties of the globular cluster to give a full picture of the environment FRB 20200120E resides in. We moved the modelling to the Methods section and added a reference to Ma et al. 2007 and to Perelmutter et al 1995 for the measured metallicity. We found no values in the literature for the other parameters that we measure. The typo in R_eff in Table 4 (previous Table 3) has been corrected. Furthermore we added new Figure 7 showing the

MCMC corner plot.

- Unnecessary content

Much of the discussion in Section 4 can be significantly refined. Rather than presenting a wider range of speculations on the source, I request that any discussion be focused on exactly which source models are disfavoured for FRB20200120E based on the association with a globular cluster. The discussion on ULXs, for example, could be dealt with in one sentence. The discussion and figure on Faraday rotation does not add anything useful and can be excluded.

Response
The discussion has been shortened significantly and some aspects have been moved to the Methods, e.g. the discussion of the MW halo's contribution to the total DM and total RM. We would like to keep the RM-discussion in the Methods as -- similarly to the DM estimate -- more estimates of this type can be expected in the future, eventually leading to a more complete picture of the MW halo's DM and RM contribution.

- Implications for other FRB sources (minor point)

Although FRB20200120E is discussed in the context of other FRB sources, as [redacted] demonstrate (their Figure 2) the duration-averaged bursts are around an order of magnitude less luminous than the brightest burst from SGR1935+2154. This is at the level where questions may be raised about whether this source is capable of producing bursts with similar energies to the more distant FRB population. Some discussion of this, or perhaps a demonstration with more data if present, would help the community in assessing the broader applicability of these findings.

Response
This is an interesting point. Obviously, if FRB20200120E were at the distance of the next closest FRB, FRB20180916B, we would not have been able to detect even the brightest of the bursts in our sample. At the same time, bursts from e.g. FRB20121102A and FRB20180916B span 3-4 orders of magnitude in spectral luminosity across a similar range in rates, i.e. log(N>E)/log(E) ~ 1. Given the 5 bursts we found in the 12.5 hrs on source, i.e. during a time when FRB20200120E was active, we would expect 0.5 bursts that are an order of magnitude brighter. Thus, it is not unexpected that we see no brighter bursts during our observations. Comparing rates and luminosities between FRB sources is difficult as energy distributions seem to change with time for one and the same source (e.g. Li et al. 20201, arXiv:2107.08205) and they differ between sources.

Referee #2 (Remarks to the Author):

[1] How do the authors know this is an FRB and not a RRAT?

Response

There are several observational properties of FRB 20200120E that distinguish this source from RRATs. The most notable are the narrow-banded emission characteristics and the so-called 'sad trombone' effect. Both these features are visible in the discovery paper of this source and in at least on burst (B2) presented in our manuscript. Emission from RRATs is broadbanded in nature with a spectral index much like that of regular pulsars. To our knowledge, the sad trombone effect has not yet been observed in RRATs. At this point, no periodicity in the emission of FRB 20200120E has been reported while RRATs seem to be slow rotators with periods on the order of seconds.

[2] Abstract: The authors state that they "propose that FRB 20200120E is a young, highly magnetised neutron star, formed via either accretion-induced collapse of a white dwarf or via merger of compact stars in a binary system." This scenario has been studied in detail by Margalit, Berger, & Metzger 2019, ApJ, 886, 110 and should be properly cited.

Response

We have added a reference to it.

[3] Figure 4: the caption ends with "It is obvious that [PR95] 30244 is resolved". However, this is not obvious at all from the profiles shown which are only marginally broader than the PSF of stellar sources in the field. This should be handled more carefully here and in the text.

Response

We agree with the referee that this was not obvious from the previous text. We have removed the mentioning in the caption and now we discuss the significant size for [PR95] 30244 in the "chance coincidence probability" from Methods, mentioning that the FWHM of the object is larger than the FWHM sizes (seeing) measured from isolated stars in the image. By subtracting the seeing values in quadrature, we derived an intrinsic FWHM of 0.42" for [PR95] 30244.

[4] Figure 6: Prospector provides uncertainty regions for the fits - these should be shown.

Response

We have added the uncertainty region for the fits.

[5] Line 435: "Subtracting the FWHMs of the isolated stars in quadrature..." I'm not convinced that this is the correct approach to measuring the size of the source. This leads to an inferred source size that is smaller than the angular resolution (seeing) of the image.

Response

Subtracting the FWHMs in quadrature works in the limit that the underlying profile and the

seeing disk are both reasonably approximated as a Gaussian distribution, which holds in this case. The convolution of two 2-D Gaussian kernels will lead to a bigger Gaussian whose FWHM is given by the quadrature sum of the individual FWHMs. The inferred source size is smaller than the seeing of the image.
In our images, the seeing kernel (as extracted from stars) can be fit by a Gaussian distribution, but is better fit by a Moffat distribution. We simulated the convolution of 2-D gaussian profiles with FWHMs ranging from 0.05 – 0.6 arcseconds and convolved them with 2-D Moffat distributions with parameters similar to those from the r-band seeing measurements (FWHM=0.57 arcsecond, beta = 4, 5, 6) and measured the FWHM of the ensuing distribution. We find that the final distribution is well-fit by a Moffat distribution. Comparing the FWHMs estimated by subtracting the seeing FWHM in quadrature to the original Gaussian FWHM, we find that the FHWMs are overestimated by ~10-15% but are otherwise a good match. The estimated FWHM for the globular cluster [PR95] 30244 of 0.42 arcseconds is thus a slight overestimate but is within the error range due to astrometric and registration errors.

Referee #3 (Remarks to the Author):

Minor comments :
Line 81: Typo. Presumable —> Presumably

Response
It is now gone after the re-structuration..

Line 322: Wording is unclear. Possibly try “Except for B1, we found all burst in the data recorded by PSRIX…”

Response
We have clarified this point to: “Bursts B2-B5 were found by blindly searching both the Effelsberg voltages and PSRIX data (Methods), while B1 was only detected in the voltage data as it occurred outside the recording times of the PSRIX instrument.”

Line 614: Word missing. There no —> There are no

Response
Fixed.

Reviewer Reports on the First Revision:

Referee #2 (Remarks to the Author):

I have read the revised version of the manuscript and I am happy to support its acceptance.

Referee #3 (Remarks to the Author):

The authors have addressed my questions, and I am happy with their revision. I recommend this article for publication.