A repeating fast radio burst source in a globular cluster

Fast radio bursts (FRBs) are flashes of unknown physical origin. The majority of FRBs have been seen only once, although some are known to generate multiple flashes. Many models invoke magnetically powered neutron stars (magnetars) as the source of the emission. Recently, the discovery of another repeater (FRB 20200120E) was announced, in the direction of the nearby galaxy M81, with four potential counterparts at other wavelengths. Here we report observations that localized the FRB to a globular cluster associated with M81, where it is 2 parsecs away from the optical centre of the cluster. Globular clusters host old stellar populations, challenging FRB models that invoke young magnetars formed in a core-collapse supernova. We propose instead that FRB 20200120E originates from a highly magnetized neutron star formed either through the accretion-induced collapse of a white dwarf, or the merger of compact stars in a binary system. Compact binaries are efficiently formed inside globular clusters, so a model invoking them could also be responsible for the observed bursts.

In total we detected five bursts from FRB 20200120E, with dispersion measures (DMs) close to the previously reported DM = 87.8 pc cm$^{-3}$. Two bursts were detected on 20 February 2021 (called B1 and B2 below), two bursts on 7 March 2021 (B3 and B4), and one burst on 28 April 2021 (B5). Bursts B2–B5 were found by blindly searching both the Effelsberg voltages and PSRIX data (Methods), whereas B1 was only detected in the voltage data as it occurred outside the recording times of the PSRIX instrument. In Fig. 1 we show the dedispersed dynamic spectra.
and frequency-averaged burst profiles. Burst fluences range from 0.13–0.71 Jy ms and total burst envelopes span only approximately 100–300 μs (Table 1). A detailed, ultrahigh-time-resolution analysis of the burst properties and energetics is presented in a companion paper10.

Correlation of the data, to produce ‘visibilities’ for interferometric imaging, was performed at the Joint Institute for VLBI ERIC. To achieve the best-possible sensitivity, we used the coherent-dedispersion mode of the software correlator SFXC11, applying DM = 87.77 pc cm⁻³, which we derived from a manual inspection of the bursts (Methods).

After an initial rough localization via delay mapping (Methods, accurate to several arcseconds), we individually imaged the five bursts, where each dataset spans only the width of each burst in time (Table 1). Given the snapshot nature of the correlations, the rather sparse arrays in each run, and the fact that the bursts only covered a fraction of the observed bandwidth, the images from the individual bursts result in elongated fringe patterns, hindering an individual, unambiguous localization of each burst at the level of the synthesized beam size (see Fig. 2a–d). Therefore, we created a dataset that is the combination of the visibilities from all bursts except B1—it was too faint to produce a useful image, and we therefore exclude it from the localization analysis. These data allowed us to unambiguously pinpoint the position of FRB 20200120E in the field (see Fig. 2e, f). The derived coordinates of FRB 20200120E in the International Celestial Reference Frame (ICRF)12 are RA (J2000) = 09 h 57 m 54.69935 s ± 1.2 milliarcsec (mas), dec. (J2000) = 68° 49′ 0.8529″ ± 1.3 mas (see Methods). These coordinates coincide with the location of the globular cluster [PR95] 3024413, which is part of the M81 globular cluster system14.

Figure 3a shows the position of FRB 20200120E with respect to [PR95] 30244 in a combined three-colour image from the Subaru Telescope made with i', r' and g' filters mapped to red, green and blue channels, respectively. The galaxy at the bottom left of [PR95] 30244 is a background SDSS galaxy at redshift z = 0.194—that is, at a z much larger than the maximum possible value (z < 0.03) based on the DM of FRB 20200120E. We performed radial fits to the brightness distribution of [PR95] 30244 using a Moffat profile15 in both RA and dec. for all three bands after fitting and subtracting a bilinearly varying background (to account for the presence of the background galaxy). The average position of the centroid of [PR95] 30244 is RA (J2000) = 09 h 57 m 54.7135 s ± 7 mas, dec. (J2000) = 68° 49′ 0.766″ ± 4 mas (statistical), well in agreement with previous measurements13 and the position of the source in the Gaia Early Data Release 3 Catalogue16,17 (Methods), in which positions are well aligned with the ICRF17.

The centre of the FRB localization is approximately 116 mas offset from the optical centre of light of [PR95] 30244 (Fig. 3b, corresponding to approximately 5% of its effective radius; see Methods). Given the astrometric uncertainty of the FRB localization (approximately 1.3 mas) and the optical image registration error with respect to the ICRF (approximately 15 mas; see Methods), we conclude that FRB 20200120E is located significantly (greater than 7σ confidence level) offset from the optical centre of light of [PR95] 30244. The optical angular size of [PR95] 30244 (0.77″; Methods) in combination with the offset of FRB 2000120E from M81 (19.6′) and the number of globular clusters predicted18 to be part of the galaxy (300 ± 100), allow us to estimate the probability of chance alignment Pcc < 1.7 × 10⁻⁴ (Methods). From such a very low Pcc value, we conclude that the association of FRB 2000120E and [PR95] 30244 is robust.

Figure 4a shows a deep continuum map that was created from the combination of the data of all VLBI observations. We find no persistent source at the location of FRB 2000120E above a 5σ confidence level (root-mean-square (r.m.s.) background noise level of 10 μJy beam⁻¹). Also shown in Fig. 4 are continuum images obtained with the Karl G. Jansky Very Large Array (VLA) at 1.5 GHz and at 340 MHz between December 2020 to January 2021 (Methods). These maps have noise levels of 6.5 μJy beam⁻¹ and 320 μJy beam⁻¹, respectively. Also here, no persistent source is detected at the position of FRB 2000120E in either of the images. For a 1.5-GHz radio flux density limit of 20 μJy (3σ) and a distance of 3.6 Mpc, we limit the radio luminosity Lν < 3.1 × 10²³ erg s⁻¹ Hz⁻¹. This luminosity limit is approximately 10² times lower than that of any other extragalactic
FRBs and almost $10^4$ times lower than the radio luminosity of the persistent source in the vicinity of FRB 20121102A.

We find no evidence of an X-ray source at the location of FRB 20200120E in archival Chandra observations (Methods). This results in a 0.5–10 keV luminosity upper limit of $2 \times 10^{37}$ erg s$^{-1}$ (3σ) at the distance of 3.6 Mpc. A detailed analysis of ongoing X-ray follow-up observations of the region will be presented in A.B.P. et al. (manuscript in preparation). Similarly, no sources are reported at the location of M81 in any of the Fermi-LAT catalogues.

Within the context of FRB models that invoke a young, highly magnetized neutron star (NS) powered primarily by the decay of its magnetic field—that is, a magnetar—it is hard to reconcile the association of FRB 20200120E with an old globular cluster using the standard core-collapse supernova formation channel of magnetars. Instead, because of their extreme stellar densities, globular clusters are known to form short-orbital-period binaries at a high rate. The nearest catalogued source (at a separation of 52') is 4FGL J0955.7 + 6940, known to be associated with M82.

### Table 1 | Burst properties

| Burst | MJD$^a$ | Fluence$^{bc}$ (Jy ms) | Peak S/N$^c$ | Peak flux density$^{bc}$ (Jy) | Width$^d$ (μs) | Gate width$^e$ (μs) |
|-------|--------|------------------------|-------------|-------------------------------|---------------|----------------------|
| B1    | 59265.883444 | 0.13 ± 0.03 | 7.8 | 0.9 ± 0.2 | 156 ± 1 | 290 |
| B2    | 59265.886091 | 0.63 ± 0.12 | 54.9 | 6.6 ± 1.3 | 62 ± 1, 93 ± 0.5 | 150 |
| B3    | 59280.696674 | 0.52 ± 0.10 | 64.5 | 7.8 ± 1.6 | 46.7 ± 0.1 | 126 |
| B4    | 59280.801733 | 0.71 ± 0.14 | 47.0 | 5.7 ± 1.2 | 117 ± 1 | 386 |
| B5    | 59332.504465 | 0.09 ± 0.02 | 11.6 | 1.4 ± 0.3 | 56.6 ± 0.1 | 173 |

$^a$Modified Julian date (MJD) corrected to the Solar System barycentre and to infinite frequency assuming a DM of 87.75 pc cm$^{-3}$, reference frequency 1.502 MHz and dispersion constant of $1/(2.41 \times 10^{-4})$ MHz$^{-1}$ pc$^{-1}$ cm$^{-3}$ s. The times quoted are dynamical times (TDB).

$^b$The receiver temperature of Effelsberg is 20 K and the telescope gain is 1.54 K Jy$^{-1}$. We additionally consider a sky background temperature of 0.8 K, by extrapolating from the 408 MHz map, using a spectral index of $-2.748$, and 3 K from the cosmic microwave background. We take a conservative 20% error on these measurements, arising because of the uncertainty in the Effelsberg receiver temperature and gain.

$^c$Computed using the frequency range over which the burst is bright.

$^d$Defined as $1/\sqrt{2}$ multiplied by the full-width at half-maximum of the autocorrelation function (ACF). Note we use the ±2σ burst width region to determine the burst fluence; see ref. 10 for details.

$^e$Width of the gate used for the interferometric correlation of each burst. For B2 the gate was centred on the first, brighter component to maximize S/N.

$^f$Width per burst component.

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Fig. 2 | Localization plots for FRB 20200120E. a-d. Normalized dirty images of the individual bursts, B2 (a), B3 (b), B4 (c) and B5 (d). e. Dirty image of the four bursts combined, produced by applying a natural weighting to the data. For visualization purposes we clip the colour scale at zero, that is, only positive peaks are displayed. The white circles are centred on the location of the globular cluster [PR95] 30244 as derived from the Subaru Telescope image in Fig. 3. Their size indicates the region that contains 90% of the optical emission of the globular cluster. The synthesized beams of each image are displayed as grey ellipses in the bottom left corner of each panel. f. The cleaned image and resulting localization of FRB 20200120E, as derived from the combined datasets of four bursts. The resulting coordinates of FRB 20200120E (highlighted by the white marker) are RA (J2000) = $09^h 57^m 54.9^s$ ± 1.2 mas, dec. (J2000) = $68^\circ 49' 0.8529''$ ± 1.3 mas.
specific rate\textsuperscript{23–25}. We thus propose that FRB 20200120E is a magnetar formed via accretion-induced collapse (AIC)\textsuperscript{26} of a white dwarf (WD) or via merger-induced collapse (MIC) of a WD–WD, NS–WD or NS–NS binary\textsuperscript{27–29}—systems that are common in globular clusters and, like FRB 20200120E, are found concentrated towards their core\textsuperscript{30} (Methods). The lack of a persistent radio or X-ray source at the position of FRB 20200120E is expected in an AIC/MIC scenario, as any emission generated during collapse fades on short time scales (less than 1 yr)\textsuperscript{7}.

The globular cluster host of FRB 20200120E also suggests some alternatives to the magnetar class of FRB models. FRB 20200120E could be a compact binary system—such as a tight WD–NS system in a pre-merger phase or a magnetized NS with a planetary companion\textsuperscript{31,32}—in which the bodies are interacting magnetically. Similarly, a binary millisecond pulsar with a strong magnetic field formed via AIC and that was subsequently spun-up via accretion\textsuperscript{33,34} could act as an FRB engine. Such a system could also be observable as a low-mass X-ray binary (LMXB)\textsuperscript{35}, as would an accreting black hole. In such an LMXB model, the radio bursts could be generated via magnetic reconnection in a relativistic jet or where the jet shocks with the surrounding medium and creates a synchrotron maser\textsuperscript{36}. Except for the most luminous LMXBs ($L_X \approx 10^{38}$ erg s\textsuperscript{-1}), our observations cannot rule out such systems. However, none of the approximately 200 Galactic LMXBs has been seen to generate FRBs. In some cases, ultraluminous X-ray sources\textsuperscript{37} have been shown to be NSs accreting at hyper-Eddington rates\textsuperscript{38}, although some may be systems with a more massive black hole primary\textsuperscript{39}. We note that ultraluminous X-ray sources have been associated with extragalactic globular clusters\textsuperscript{40}, but such systems are ruled out by our X-ray limit unless their luminosity varies in time by more than two orders of magnitude. Additionally, the association with a globular cluster rules out a high-mass X-ray binary origin of FRB 20200120E and the projected offset of approximately 2 pc from the centre of light of [PR95] 30244 excludes the association of FRB 20200120E with, for

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**Fig. 3 | Optical images of the FRB 20200120E host and surrounding field.** a, 40″ × 40″ $g'$-, $r'$- and $i'$-band image of [PR95] 30244 acquired with Hyper Suprime-cam. The small red ellipse is centred at the location of FRB 20200120E. b, Magnified $r'$-band image of [PR95] 30244. The grey circle represents the estimated position of the centre of [PR95] 30244 and its 3σ uncertainty (dominated by the optical-to-radio reference frame tying). The small red ellipse is the same as in a, and represents the 10σ positional uncertainty region of FRB 20200120E. c, d, Cross-sections of the brightness distribution of the cluster (blue solid lines) with the fitted Moffat profile overlaid in black. Indicated in solid grey lines are the PSFs as measured from stars in the images. Note that scatter in the PSFs is smaller than the linewidth.

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**Fig. 4 | Continuum maps of the field around FRB 20200120E.** a, 1.4-GHz EVN continuum image after combining the three epochs (EK048B, EK048C and EK048F). b, 1.5-GHz Realfast image. c, 340-MHz VLITE continuum image. The red circles indicate the 10σ (for EVN) and 1,000σ (for Realfast, VLITE) positional uncertainty region of FRB 20200120E. Note the very different scales between the three panels. We clip all values below zero and above 60 μJy beam\textsuperscript{-1} (EVN), 50 μJy beam\textsuperscript{-1} (Realfast) and 3 mJy beam\textsuperscript{-1} (VLITE) for visualization purposes. The black ellipse in the bottom left corner of each image indicates the synthesized beam size and position angle.
example, a massive (much greater than 10M⊙) stellar mass black hole or a putative intermediate mass black hole at the core of [PR95] 30244.

The association of FRB 20200120E with a globular cluster adds to the diversity of environments in which repeating FRBs have been found. Although FRB 20121102A resides in a dwarf galaxy41, the host of FRB 20180916B is a spiral galaxy42 and FRB 20201124A was localized to a massive star-forming galaxy42. Previously localized repeaters have been associated with nearby star-forming regions43–46, favoring the core-collapse supernova channel for the formation of young magnetars, as the rate of AIC and MIC is much lower. The lack of a persistent radio source for all but FRB 20121102A may suggest a range in the possible ages of such magnetars. In a globular cluster environment, however, the recent core-collapse of a massive star is very unlikely. Thus, this suggests a diversity in formation channels for magnetars as FRB engines.

Online content

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Methods

Observations and data reduction

**VLBI observations.** As part of our ongoing very long baseline interferometry (VLBI) campaign called PRECISE (Pinpointing Repeating Chime Sources with the EVN), we observed the field centred on the coordinates from the discovery of FRB 20200120E: RA (J2000) = 09 h 57 m 56.688 s, dec. (J2000) = 68° 49′ 31.8″. The quoted 90% confidence interval of radius ~1.5″ is well covered by the field of view of the ad hoc interferometric array we used to observe, which comprises dishes that are also part of the EVN. We observed the field 15 times between February and May 2021 (Extended Data Table 1), with burst detections in the data that were taken on 2021 February 20 UT 17:00–22:00 (project code PR141A), 2021 March 7 UT 15:45–20:45 (PR143A), and 2021 April 28 UT 11:00–22:00 (PR158A). We observed in the 21-cm band (~1.4 GHz) with slightly different array setups in each run. Depending on the capabilities at each station, we recorded either 128 or 256 MHz of total bandwidth, divided into 8 or 16 subbands of 16 MHz each. The participating stations and their respective frequency coverage are summarized in Extended Data Table 2. We ran regular phase-referencing observations with a cycle time of 7.5 min; that is, 5.5 min on target and 2.0 min on the phase calibrator (J0955 +6903, at ~0.32″ separation). In total, we spent 2.93 h on the target field in each of PR141A and PR143A, and 6.73 h in PR158A. The calibrator source J1048 +7143 served as fringe finder and bandpass calibrator and was observed twice for 5 min in each run. For verification and single-dish time-domain calibration purposes we observed the pulsar B0355 +54 for 2 min in PR141A and PR143A. In PR158A the pulsar B2235 +58 was observed for 5 min for the same reason.

We recorded raw voltages (’baseband’ data, dual circular polarization, 2-bit sampling) in VDF19 or MarkSB50 format at all stations. At Effelsberg we also recorded total intensity filterbanks with the PSRIX pulsar backend in parallel to the voltage data. These data span the frequency range of 1255–1505 MHz with a time and frequency resolution of 102.4 μs and 0.49 MHz, respectively. Similarly, at SRT we also recorded in parallel baseband data and total intensity filterbanks (with the local Digital Filter Bank system, DFB). These DFB-filterbanks have a time and frequency resolution of 128 μs and 1 MHz, respectively, covering the frequency range of 1140.5–2163.5 MHz out of which we search the usable range of 1210.5–1739.5 MHz.

The data from both Effelsberg and SRT were searched for bursts in two independent pipelines. The baseband data were processed with the pipeline outlined in ref. 51, which converts the raw voltages to filterbank format (in this case, total intensity with time resolution 64 μs and frequency resolution 125 kHz) and searches those with Heimdall within ±50 pc cm⁻³ of the expected DM = 87,818 pc cm⁻³, as found in ref. 51. The burst candidates are classified as either radio frequency interference (RFI) or potential FRBs using the neural network classifier FETCH53. The filterbanks as recorded with the respective pulsar backends were searched with a pipeline that uses the PRESTO suite of tools54,55 and a real-time system to search the incoming voltage stream for dispersed transients. All VLITE data were processed within the VLITE-Fast GPU-based real-time system to search the incoming voltage stream for dispersed transients. For imaging purposes, primary calibration and editing for each day of visibility data were carried out with the automated VLITE processing pipeline. Owing to radio interference from satellites at the upper end of the band, the final usable bandwidth was 38.2 MHz centred at 340.85 MHz. The data were subsequently combined, imaged and self-calibrated in amplitude and phase using the Obit task MFImage63.

**VLA.** We observed the field of FRB 20200120E with the Karl G. Jansky Very Large Array (VLA) as part of a programme to localize repeating FRBs identified by CHIME/FRB (program 20B 280). The field was observed in five 1-hour blocks from 2020 December 29 through to 2021 January 18. Data were recorded in parallel at both 1.5 GHz and 340 MHz. The VLA antennas were arranged in the A configuration, which provides baseline lengths up to 30 km and a typical spatial resolution of 1.3″ and 6.0″ at 1.5 GHz and 340 MHz, respectively. The total on-target integration time amounts to 200 min.

Realfast. Visibility data from the VLA observations were recorded with a sampling time of 3 s from 1 to 2 GHz. Simultaneously, a copy of the data with sampling time of 10 ms was streamed into the Realfast system55. We used Realfast to search this data stream for FRBs in real time. The typical α sensitivity of the VLA is 5 mJy beam⁻¹ in 10 ms. The standard (slow) visibility data were analysed to search for persistent emission associated with the FRB location. We calibrated the data with the VLA calibration pipeline (version 2020.1) using 3C147 as a flux calibrator. Calibrated visibilities for all five epochs were combined and imaged with CASA (version 6.1).

We imaged the data with robust weighting of 0.5 and removed baselines shorter than 100 km to reduce the effects of RFI. This produced an image with a synthesized beam size of 2″ by 1″ with position angle of 126°. The sensitivity in the combined image is 6.5 mJy beam⁻¹, which is consistent with expectations given the usable bandwidth of 400 MHz.

**VLITE.** The VLA Low-band Ionosphere and Transient Experiment VLITE64 is a commensal instrument on the VLA that records and correlates data from a 64-MHz sub-band at a central frequency of ~340 MHz. It operates on up to 18 antennas during nearly all regular VLA operations. All VLITE data were processed within the VLITE-Fast GPU-based real-time system to search the incoming voltage stream for dispersed transients. For imaging purposes, primary calibration and editing for each day of visibility data were carried out with the automated VLITE processing pipeline. Owing to radio interference from satellites at the upper end of the band, the final usable bandwidth was 38.2 MHz centred at 340.85 MHz. The data were subsequently combined, imaged and self-calibrated in amplitude and phase using the Obit task MFImage63.
To reduce artefacts from the bright extended radio galaxy M82 located -1° northwest of the target position, baselines shorter than 4.0 kλ were removed at this point. The final image was created in WSClean\textsuperscript{4c}, and corrected for the offset primary beam response of VLITE. The image has an r.m.s. of 320 μJy beam\textsuperscript{-1}, and a beam of 10.1" by 3.6" at a position angle of 132°.

Archival optical and high-energy data. Hyper Suprime-Cam. The field around M81 has been well observed over the years by multiple telescopes. We retrieved archival data from the Hyper Suprime-Cam on the 8.1-m Subaru telescope\textsuperscript{4d} using the SMOKA interface. We chose images with seeing better than 0.7". We processed the g′, r′, and i′ band images with the hscpipe\textsuperscript{8}.4 pipeline\textsuperscript{4e}. The pipeline uses the PanSTARRS catalogue PSC\textsuperscript{9} as an astrometric and photometric reference. The typical astrometric residuals were ~50–60 mas.

Gaia. [PR95] 30244 also appears in the Gaia Early Data Release 3 Catalogue\textsuperscript{10,11} with source ID 1070264274879949184, and position RA (J2000) = 09 h 57 m 54.71402 s ± 1.6 mas, dec. (J2000) = 68° 49′ 0.7775″ ± 1.7 mas. This position is consistent (within <3σ confidence level) with the one we have derived from the Hyper Suprime-Cam data. The observed offset allowed us to estimate the possible systematic uncertainties in the optical image registration error (15 mas; by adding in quadrature the observed offset between the the Gaia position and the one we determined, plus the uncertainties on the positions).

Chandra X-ray Observatory. Several deep archival X-ray observations are available for the field around M81 from XMM and Chandra. We selected the archival observation with the longest exposure time that covers the location of FRB 20200120E, a 26-ks Chandra observation (Obs. ID 9540), taken with ACIS in FAINT mode\textsuperscript{12}, to probe for an X-ray source. The data were reduced using CIAO version 4.12\textsuperscript{13} following standard procedures. As the source was located about 14′ off-axis, events were extracted in a large 10″-radius region centred on the position of FRB 20200120E. We also extract events from a 60″-radius region away from the source at a similar off-axis angle to estimate the background count rate. The X-ray count-rate in the source extraction region, 4.4 × 10\textsuperscript{-5} counts s\textsuperscript{-1} arcsec\textsuperscript{-2}, is consistent with the background count rate of 3.9 × 10\textsuperscript{-5} counts s\textsuperscript{-1} arcsec\textsuperscript{-2}. To place a limit on an X-ray source at the location of FRB 20200120E we use the Bayesian method of ref. \textsuperscript{14}, which results in a 0.5–10 keV source count rate upper limit of 1 × 10\textsuperscript{-5} counts s\textsuperscript{-1} (3σ). Taking into account the spectral response for the off-axis location of the source (via an ancillary response file created by the CIAO tool specextract), and assuming a photoelectrically absorbed power-law source spectrum with a spectral index f\textsuperscript{−1} = 2 and a hydrogen column density of N\textsubscript{H} = 10\textsuperscript{19} cm\textsuperscript{-2}, this count rate limit corresponds to a 0.5–10 keV absorbed flux upper limit of 1 × 10\textsuperscript{-17} erg cm\textsuperscript{-2} s\textsuperscript{-1}.

Fermi-LAT. The Large Area Telescope (LAT) onboard the Fermi satellite provides a uniform sensitivity survey of the whole sky in the energy range between 100 MeV and 300 GeV. We searched all of the publicly available catalogues for counterparts up to the latest published\textsuperscript{15} release, 4FGL-DR2, with null results. However, even the most luminous known Galactic globular cluster (Terzan5), whose luminosity is (42.4 ± 1.5) × 10\textsuperscript{-10} erg s\textsuperscript{-1} in the 0.1–100 GeV energy range\textsuperscript{16,17}, would have a γ-ray flux of only (2.00 ± 0.07) × 10\textsuperscript{-16} erg cm\textsuperscript{-2} s\textsuperscript{-1} at the distance of M81. This is nearly three orders of magnitude dimmer than the faintest power-law source spectrum with a spectral index of Γ = 2 and a hydrogen column density of 10\textsuperscript{22} cm\textsuperscript{-2}.

Analysis

Dispersion measure refinement. To refine the DM for further analysis, we maximized the signal-to-noise ratio (S/N) of a very narrow spike in B3\textsuperscript{18} (Fig. 1g) and find DM = 87.7527 ± 0.0003 pc cm\textsuperscript{-3}. This value is comparable to, but formally deviates from DM = 87.818 ± 0.007 pc cm\textsuperscript{-3} found in ref. \textsuperscript{19}, where a weighted average of three bursts was used. Possible explanations for this discrepancy are the lack of short-timescale structure in the CHIME/FRB bursts\textsuperscript{20}, the potential for non-dispersive time-frequency drifting\textsuperscript{21} or a time-variable DM.

Milliarcsecond localization of FRB 20200120E. We imaged both the individual bursts separately, as well as a dataset produced by the combination of all individual burst visibilities. Figure 2a–d displays the ‘dirty’ maps (that is, the inverse Fourier transform of the visibilities without applying any deconvolution, that is ‘CLEANing’) of the bursts that were detectable in the correlated data, using a natural weighting of the data. B1 was too faint to produce a useful image, and we therefore exclude it from the localization analysis. B3 was only detected in the lower half of the observed band, where most of the antennas were not recording (see Extended Data Table 2). We therefore only used data from this part of the band. Figure 2e shows the dirty map of the combined data of the visibilities from all bursts. In this map we obtained an emission pattern consistent with the one expected from the dirty beam (the inverse Fourier Transform of a point-like source), allowing us to unambiguously identify the position of FRB 20200120E. The observed emission reached a 1σ confidence level, and the secondary sidelobes in the fringe pattern were ~66% of the peak emission. This provided a robust localization in the map, as it would require a noise fluctuation of ±7σ to produce such peak emission. We also conducted different approaches during the imaging of the data: different weighting schemes and selecting different subsets of antennas in the array. The derived position of FRB 20200120E was robust across all these approaches. Figure 2f displays the final, ‘CLEANed’, image of the combined bursts.

The final coordinates of FRB 20200120E are RA (J2000) = 09 h 57 m 54.69935 s ± 1.2 mas, dec. (J2000) = 68° 49′ 0.8529″ ± 1.3 mas. We note that the quoted uncertainties reflect the statistical uncertainties from the measured position of FRB 20200120E (0.7 and 0.4 mas in RA and dec., respectively), the uncertainties in the absolute International Celestial Reference Frame position of the phase calibrator (J0955 + 6903; 0.11 mas), and the systematic uncertainty associated with the phase-referencing technique\textsuperscript{22} of ~0.9 and 1.2 mas, in RA and decl., respectively.

We combined the continuum VLBI data from the three epochs to produce a deep image of the field around FRB 20200120E to search for persistent emission. No significant sources above a 5σ confidence level (with an r.m.s. of 10 μJy beam\textsuperscript{-1}) are detected on milliarcsecond scales (Fig. 4a). In the VLA data taken at 1.5 GHz (Fig. 4b), we did identify two sources with peak brightness of 110 μJy beam\textsuperscript{-1} and 73 μJy beam\textsuperscript{-1}, and offset by 6″ and 9″, respectively. The projected density of radio sources of this brightness is roughly 1,000 to 3,000 per square degree\textsuperscript{23}. Therefore, we expect between 1 and 3 sources within 1″ of FRB 20200120E by chance. The closer of the two nearby radio sources is within 0.2″ of a PSI source with t = 21.3 mag. This host galaxy has a photometric redshift in the PSI STRM catalogue\textsuperscript{24} of 0.67 ± 0.2, so it is most probably a background galaxy. The other identified radio source has no PSI counterpart. We note that neither of these two sources exhibit significant compact emission on milliarcsecond scales.

[PR95] 30244 and chance coincidence probability. We measured the full-width at half maximum (FWHM; ‘seeing’) of the coadded i′, r′, and g′ images of [PR95] 30244 to be 0.63″, 0.57″ and 0.62″, respectively, using profile fits to bright, isolated stars. The brightness distribution of [PR95] 30244 has an FWHM of 0.77″, 0.70″, and 0.75″ in the same three images. Subtracting the FWHMs of the isolated stars in quadrature, we estimate that the intrinsic FWHM of [PR95] 30244 is about 0.42″, corresponding to about 7.4 pc at a distance of 3.63 Mpc.

To estimate the probability of chance coincidence\textsuperscript{25} for an M81 globular cluster in the FRB localization region, we use a circular localization region with a radius (R) = max[2r_{eff} of [PR95] 30244, maximum seen size of [PR95] 30244 in the Hyper Suprime-images] = 0.77″. Perelmuter & Racine\textsuperscript{26} parameterized the projected areal number density (n_{gc} arcmin\textsuperscript{-2}) of the M81 globular clusters as a function of their angular offset from M81 (r, in arcmin) as log_{10}(n_{gc}) = -2.07 × log_{10}(r) + 0.82 ± 0.05, for 0 ≤ log_{10}(r) ≤ 1.4. At the offset of FRB 20200120E from
MS1 (19.6''), $\rho_{\text{gc}} = 0.014$ arcmin$^{-2}$ = 3.8 $\times$ 10$^{-4}$ arcsec$^{-2}$. Assuming a Poisson distribution of MS1 globular clusters at $\tau = 19.6''$, the probability of finding at least one globular cluster by chance within a radius $R$ is given by $P_c = 1 - \exp(-\pi \rho_{\text{gc}} R^2) = 7 \times 10^{-8}$. A more conservative estimate of $P_c$ can be derived by assuming that all the predicted 300 $\pm$ 100 MS1 globular clusters are uniformly distributed within the angular area of radius $\tau = 19.6''$ so that $\rho_{\text{gc}} = (4.6-9.2) \times 10^{-4}$, and consequently $P_c \approx (0.85-1.7) \times 10^{-8}$. From such a very low $P_c$ value, we conclude that the association of FRB 20200120E and [PR95] 30244 is robust.

Modelling of [PR95] 30244. To estimate important physical properties of [PR95] 30244, such as its stellar mass, metallicity, stellar population age and V-band extinction, we used the Prospector code for stellar population inference. We modelled the SDSS photometry (Extended Data Table 3, from the SDSS DR12 catalogue) of [PR95] 30244 and fitted a five-parameter (Extended Data Table 4) 'delayed-tau' model for the star formation rate $\Sigma_F(t) \propto \exp(-t/\tau)$, where $t$ is the time since the formation epoch of the galaxy, and $\tau$ is the characteristic decay time of the star-formation history of [PR95] 30244. As we are modelling a globular cluster, we did not include nebular line emission but only enabled a dust emission model in our fitting. The best-fit spectral energy distribution (SED) profile of [PR95] 30244 is shown in Extended Data Fig. 2. Prospector also enables Markov Chain Monte Carlo (MCMC) sampling of the posterior to estimate uncertainty in the best-fit values of the physical properties of [PR95] 30244. We show the corner plot of the MCMC analysis in Extended Data Fig. 3 and list the results in Extended Data Table 3. Using the relation $\log[\text{Fe/H}] = 1.024 - \log(Z/Z_c)$, we estimate that the [Fe/H] of [PR95] 30244 is $-1.83^{+0.86}_{-0.87}$, which is in good agreement with earlier estimates. We can get an estimate of the velocity dispersion ($\sigma_v$) of [PR95] 30244 using the virial theorem: $\sigma_v^2 = 2GM/Reff$, where $G$ is the gravitational constant. Using the $M$ and $R_e$ values of [PR95] 30244 from Extended Data Table 1, we estimate $\sigma_v = 22$ km s$^{-1}$.

Possible MIC models for the formation of FRB 20200120E. The most probable of the MIC models is that of a merging WD–WD system as those dominate the cores of globular clusters, whereas an NS–NS progenitor system is less probable. A typical globular cluster with a total mass of $(2 \times 10^5)$M$_\odot$ can host 10–20 millisecond pulsars (MSPs) formed via AIC or MIC. At birth, such NSs would be extreme objects with high rotation rates and strong magnetic fields, potentially capable or generating FRBs. We note that the metallicity limit (log[Fe/H] > $-0.6$) set for most possible MIC models for the formation of FRB 20200120E, but only enabled a dust emission model in our fitting. The best-fit spatial gradient in the region, Extended Data Fig. 1). Using these estimates, we limit the Milky Way halo contribution to the FRB sight line, which is poorly constrained by current observations, to DM$^{\text{Halo}} = DM - DM^{\text{ISM}} - DM^{\text{GC}} - DM^{\text{M81}} \leq 32-42$ pc cm$^{-3}$. This is well in line with the models of Yamasaki & Totani, which predict DM$^{\text{Halo}} = 10-30$ pc cm$^{-3}$, but lower than predicted in some other models.

Similar considerations are also applicable for the rotation measure RM $\approx -36.9$ rad m$^{-2}$ as determined in the companion paper. The Galactic contribution along the line of sight to FRB 20200120E is RM $\approx -17 \pm 4$ rad m$^{-2}$ (Extended Data Fig. 1). The contribution of the IGM is probably minor, leaving only the MW halo, the M81 halo and the local environment of FRB 20200120E as contributing sources. The RM of the MW and M81 halo are probably small (|RM| < 20 rad m$^{-2}$), constraining RM$^{\text{M81}}$ to the range [20, 60] rad m$^{-2}$. This is comparable to earlier results for FRB 20180916B (RM $\approx -115$ rad m$^{-2}$) but three orders of magnitude lower than the (highly variable) RM of FRB 20121102A. This indicates that models of FRB sources do not necessarily require extreme magneto-ionic environments, unless the magnetic fields along the line of sight to both FRB 20200120E and FRB 20180916B are strongly tangled, such that they result in a low net RM. More probable though is that FRB 20121102A resides in a very different environment, giving rise to its observed properties.

Data availability

The datasets generated from the EVN observations and analysed in this study are available at the Public EVN Data Archive under the experiment codes EKO48B, EKO48C and EKO48F. The calibrated maps, plotting scripts and further data used in this manuscript are available at https://doi.org/10.5281/zenodo.5708237.

Code availability

The codes used to analyse the data are available at the following sites: AIPS (http://www.aips.nrao.edu/index.shtml), CASA (https://casa.nrao.edu), Difmap (https://science.nrao.edu/facilities/vla/docs/manuals/oss2013a/post-processing-software/difmap), DSPSR (http://dspsr.sourceforge.net), FETCH (https://github.com/devanshkv/fetch), Heim-dall (https://sourceforge.net/projects/heimdall-astro), IRAF (https://iraf-community.github.io), PRESTO (https://github.com/scottansom/preso), PSRCHIVE (http://psrchive.sourceforge.net), and Sp5 (https://github.com/danielmichilli/sp5).

50. Whitney, A. et al. VLBI data interchange format (VDF). In Sixth International VLBI Service for Geodesy and Astronomy. Proceedings from the 2010 General Meeting (eds Navarro, R. et al.) 190–196 (NASA, 2010).
51. Whitney, A. The Mark 5B VLBI data system. In Proc. 7th European VLBI Network Symp. on VLBI Scientific Research and Technology (eds Bachiller, R. et al.) 251–252 (EVN, 2004).
52. Kirsten, F. et al. Detection of two bright radio bursts from magnetar SGR 1935+2154. Nat. Astron. 5, 454–452 (2021).
53. Agarwal, D., Aggarwal, K., Burke-Spolaor, S., Lorimer, D. R. & Garver-Daniels, N. FETCH: a deep-learning-based classifier for fast transient classification. Mon. Not. R. Astron. Soc. 497, 1661–1674 (2020).
54. Ransom, S. M. New Search Techniques for Binary Pulsars. Ph.D thesis, Harvard Univ. (2001).
55. Ransom, S. PRESTO: Pulsar Exploration and Search Toolkit. Astrophysics Source Code Library http://ascl.net/1007.017 (2011).
56. Michilli, D. et al. Single-pulse classifier for the LOFAR Tied-Array All-sky Survey. Mon. Not. R. Astron. Soc. 480, 3457–3467 (2018).
57. Greisen, E. W. AIPS, the VLA, and the VLBA. In Information Handling in Astronomy – Historical Vistas (ed. Heck, A.) 109–125 (Kluwer Academic, 2003).
58. Shepherd, M. C., Pearson, T. J. & Taylor, G. B. DIFMAP: an interactive program for synthesis imaging. Bull. Am. Astron. Soc. 26, 987–989 (1994).
59. Law, C. J. et al. Real-time, commensal fast transient surveys with the Very Large Array. Astrophy. J. Suppl. Ser. 236, 8 (2018).
60. Polisensky, E. et al. Exploring the transient radio sky with VLITE: early results. Astrophy. J. 832, 60 (2016).
61. Clarke, T. E. et al. Commensal low frequency observing on the NRAO VLA: VLITE status and future plans. In Proc. SPIE 9906: Ground-based and Airborne Telescopes VI (eds Hall, H. J. et al.) 99065B (SPIE, 2016).
62. Bethapudi, S. et al. The first fast radio burst detected with VLITE-Fast. Res. Not. Am. Astron. Soc. 5, 46 (2021).
63. Cotton, W. D. Obit: a development environment for astronomical calculations. Publ. Astron. Soc. Pac. 120, 439–448 (2008).
and A. B. P. searched the Fermi catalogues. Z. P. assisted with the reduction and analysis of the correlated data. C. B. assessed the optical registration errors of the Subaru and Gaia images. D. M. H. searched the PSRIX and DFB data for bursts. U. B. coordinated and performed the observations at Effelsberg. V. B. coordinated and performed the observations at Irbene. M. Burgay helped commission the dual recording mode at SRT. S. T. B. coordinated and performed the observations at Noto. J. E. C. supported the observations at Onsala. A. C. implemented the dual recording mode at SRT and performed some of the observations. R. F. supports the observations at Toruń. O. F. wrote observing schedules. M. P. O. coordinated and performed the observations at Torun. R. K. assisted with the dual recording at Effelsberg. M. A. K. supports the observations at Badary, Svetloe and Zelenchukskaya. M. L. supported the observations at Onsala and assisted with the manuscript. G. M. coordinated and performed the observations at Medicina. A. M. coordinated and performed the observations at Badary, Svetloe and Zelenchukskaya. A. G. M. supports the data transfer of the observations at Badary, Svetloe and Zelenchukskaya. O. S. O.-B. wrote observing schedules. A. P. supported the observations at SRT. G. S. ran most of the observations at SRT. N. W. and J. Yuan coordinated and performed the observations at Urumqi. V. M. K. played a significant coordination role that enabled these results. All other co-authors contributed to the CHIME/FRB discovery of the source or the interpretation of the analysis results and the final version of the manuscript.

**Competing interests** The authors declare no competing interests.

**Additional information**

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Extended Data Fig. 1 | DM and rotation measure (RM) maps around FRB 20200120E. a, Expected Galactic DM contribution (background) according to the YMW16 model disk contribution only; the DM of FRB 20200120E (pentagon) and the DMs of known pulsars from the ATNF Pulsar Catalogue in this field (circles); b, Physical Galactic Faraday depth $\phi_g$ (background); the RM of FRB 20200120E (pentagon) and Galactic pulsars with a known RM (circles). We assume that the RM of FRB 20200120E is $\sim$36.9 rad m$^{-2}$. 
Extended Data Fig. 2 | Modelling the SED of [PR95] 30244. The Milky Way extinction corrected flux densities of [PR95] 30244 in different wavelength bands are plotted, along with the best-fit Prospector model spectrum. To assess the quality of the Prospector model, the modelled and actual photometric data are also shown. The best-fit model profile is used to estimate the physical properties of [PR95] 30244 stated in Extended Data Table 3. Finally, the shaded region around the best-fit profile is the 1σ uncertainty region.
Extended Data Fig. 3 | MCMC simulation corner plot. The posterior probability distributions are shown for each of the five model parameters along the diagonal panels, and the correlations between model parameter posteriors are shown along the columns. Above each probability distribution, the median of the parameter posterior is printed, along with the 1σ error bars.
## Extended Data Table 1 | Time ranges of PRECISE runs targeting FRB 20200120E between February and May 2021

| Observation Project code | EVN Project code | Start MJD | Stop MJD |
|--------------------------|------------------|-----------|----------|
| PR141A*                  | EK048B           | 59265.708 | 59265.916 |
| PR143A*                  | EK048C           | 59280.656 | 59280.864 |
| PR144A                   |                  | 59283.792 | 59284.000 |
| PR145A                   |                  | 59289.750 | 59289.958 |
| PR146A                   |                  | 59295.667 | 59295.875 |
| PR153A                   |                  | 59314.887 | 59314.972 |
| PR158A*                  | EK048F           | 59332.458 | 59332.916 |
| PR159A                   |                  | 59336.708 | 59337.000 |
| PR160A                   |                  | 59341.833 | 59342.072 |
| PR161A                   |                  | 59344.771 | 59344.875 |
| PR162A                   |                  | 59346.646 | 59346.895 |
| PR163A                   |                  | 59347.417 | 59347.625 |
| PR164A                   |                  | 59351.917 | 59352.166 |
| PR165A                   |                  | 59358.917 | 59359.166 |
| PR166A                   |                  | 59360.708 | 59360.916 |

*Epoch with detection.
## Extended Data Table 2 | Set-ups at the different stations during observations used in the analysis

| Telescope            | Frequency coverage [MHz] | Station project code | EVN project code |
|----------------------|--------------------------|----------------------|-----------------|
| Effelsberg (Ef)      | 1254 – 1510              | 94-20                | EK048B/C/F†      |
| Medicina (Mc)        | 1350 – 1478              | 44-20                | EK048B/C/F†      |
| Noto (Nt)            | 1318 – 1574              | 44-20                | EK048 C          |
| Irbeue (Ir)          | 1382 – 1510              | –                    | EK048B/C/F       |
| Toruflu (Tr)         | 1254 – 1510              | DDT*                 | EK048B/C/F†      |
| Westerbork (Wb)      | 1382 – 1510              | DDT*                 | EK048B/C/F       |
| Urumqi (Ur)          | 1382 – 1510              | DDT*                 | EK048 C/F        |
| Sardinia (Sr)        | 1360 – 1488              | 44-20                | EK048 F          |
| Onsala (Ob)          | 1382 – 1510              | DDT*                 | EK048B F†        |
| Badary (Bd)          | 1382 – 1510              | DDT*                 | EK048 F          |
| Svelloe (Sv)         | 1382 – 1510              | DDT*                 | EK048 F          |
| Zelenchukskaya (Zc)  | 1382 – 1510              | DDT*                 | EK048 F          |
| VLA-VLITE            | 320 – 384                | 20B-280              | –               |
| VLA-Reallast         | 1300 – 1700              | 20B-280              | –               |

*Director’s Discretionary Time.
†Only stations recording the part of the band where the burst (B5) was detected with significant emission.
‡Only one sub-band overlapping with the part of the band where the burst (B5) was detected with significant emission.
Extended Data Table 3 | Notable properties of [PR95] 30244

| Property                     | Value          | Reference |
|------------------------------|----------------|-----------|
| Metallicity log(Z/Z_⊙)      | $-1.74_{-0.10}^{+0.09}$ | this work |
| Metallicity [Fe/H]           | $-1.83_{-0.07}^{+0.07}$ | this work |
| Stellar mass log(M/M_⊙)     | $5.7_{-0.22}^{+0.19}$ | this work |
| Effective radius (R_eff/pc)  | 3.7            | this work |
| Age (Gyr)                    | $9.13_{-0.18}^{+0.14}$ | this work |
| (u − r)_⊙ (AB mag)          | 1.96(2)        | 80        |
| E(V − B)                     | $0.20_{-0.01}^{+0.1}$ | this work |
| σ_r (km s$^{-1}$)            | 22             | this work |
| Absolute r-band mag. (AB)    | $-8.4$         | —         |
| Luminosity distance (Mpc)    | 3.6            | 101       |

Refs. 80, 101

*Milky Way extinction is corrected using a reddening map 102.
†Using R_v = 3.1.
Extended Data Table 4 | Broadband SDSS filters used to model the SED of [PR95] 30244

| Instrument | Filter | Effective Wavelength [Å] | Flux density [maggie]* |
|------------|--------|--------------------------|------------------------|
| SDSS       | u      | 3546                     | 2.92×10^-9             |
|            | g      | 4670                     | 1.05×10^-8             |
|            | r      | 6156                     | 1.77×10^-8             |
|            | i      | 7472                     | 2.04×10^-8             |
|            | z      | 8917                     | 2.33×10^-8             |

*The flux densities are assigned a 20% fractional uncertainty. Note that 1 maggie is defined as the flux density in Jansky divided by 3,631.
Extended Data Table 5 | Free parameters and their associated priors for the Prospector ‘delayed tau’ model

| Parameter | Description                        | Prior               |
|-----------|------------------------------------|---------------------|
| log(M/M_☉) | total stellar mass formed          | uniform: min=3, max=7 |
| log(Z/Z_☉) | stellar metallicity                | top-hat: min=-3.5, max=0 |
| dust2     | diffuse V-band dust optical depth  | top-hat: min=-0.0, max=2.0 |
| t_{40}    | age of [PR95] 30244                | top-hat: min=0.1, max=13.8 |
| τ         | e-folding time of the SFH          | uniform: min=0.1, max=30 |