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Research Article

Keywords: transients, fast radio burst - methods, statistical - stars, magnetars

Posted Date: April 6th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1513169/v1

Luminosity distribution of fast radio bursts from CHIME/FRB Catalog 1 by the updated Macquart relation

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Abstract

Fast radio bursts (FRBs) are extremely strong radio flares lasting several milliseconds and come from unidentified objects at cosmological distances, most of which are only seen once. Based on recently published data in the CHIME/FRB Catalog 1 in the frequency bands 400-800 MHz, we analyze 226 apparently singular FRBs with low dispersion measure (DM) and find that the distribution of their luminosity follows a lognormal form according to statistical tests. In our luminosity measurement, the FRB distance is estimated by using the Macquart relation which was obtained for 8 localized FRBs, and we find it still applicable for 18 sources after adding the latest 10 new localized FRBs. In addition, we test the validity of the luminosity distribution up to the Macquart relation and find that the lognormal form feature decreases as the uncertainty increases. Moreover, we compare the luminosity of these apparent non-repeaters with that of the previously observed 10 repeating FRBs also at low DM, noting that they belong to different lognormal distributions with the mean luminosity of non-repeaters being two times greater than that of repeaters. Therefore, from the two different lognormal distributions, different mechanisms for FRBs can be implied.

Keywords: transients: fast radio burst - methods: statistical - stars: magnetars

1 Introduction

Fast radio bursts (FRBs) are very strong radio sparks lasting a couple of milliseconds, which are mostly confirmed to be from objects at cosmic distances, which perhaps noticed in 1980 (Linscott and Erkes, 1980). The FRB phenomenon was systematically studied by Lorimer et al (2007), and then Thornton et al (2013) discovered several more sources in 2013. Subsequently, this field developed rapidly (Lorimer, 2018; Zhang, 2020; Petroff et al, 2021), including the first localized repeating FRB 121102 (Spitler et al, 2016; Chatterjee et al, 2017), the first FRB-like signal-FRB 200428 from the Galactic soft gamma repeater (SGR) 1935+2154 (Bochenek et al, 2020; CHIME/FRB Collaboration et al, 2020; Lin et al, 2020; Li et al, 2021a) and FRB 20200120E in M81 (Bhardwaj et al, 2021). In addition, with further study, several research efforts showed that FRBs may be periodically active (FRB 180916: 16 day and FRB 121102: 157 day) (Chime/Frb Collaboration et al, 2020; Rajwade et al, 2020) and emit periodic signals (FRB 20191221A: 216.8 ms, FRB 20210206A: 2.8 ms, and FRB 20210213A: 10.7 ms) (The CHIME/FRB Collaboration et al, 2021b). Meanwhile, thanks to the completion of advanced radio instruments like the Canadian Hydrogen Intensity Mapping Experiment (CHIME) (CHIME/FRB Collaboration et al, 2019a,b, 2020; Chime/Frb Collaboration et al, 2020; The CHIME/FRB Collaboration et al, 2021a,b), Australian Square Kilometre Array Pathfinder (ASKAP) (Shannon et al, 2018; Kumar et al, 2019), and Five-hundred-meter Aperture Spherical radio Telescope (FAST) (Li et al, 2018; Zhu et al, 2020; Luo et al, 2020b; Lin et al, 2020; Niu et al, 2021; Li et al, 2021b), the data of FRBs, as well as their diverse properties, have dramatically increased. For example, the 1652 and 849 bursts related to FRB 121102 were observed by FAST (Li et al, 2021b) and Arecibo (Jahns et al, 2022), respectively, and CHIME released the CHIME/FRB Catalog 1[1] (The CHIME/FRB Collaboration et al, 2021a) recently.

Before the CHIME/FRB Catalog 1 came out in June of 2021 (The CHIME/FRB Collaboration et al, 2021a), the FRB Catalogue (FRBCAT)[2] was mostly used to study the statistical properties of FRBs (Petroff et al, 2016). Up to now, 129 FRB sources were published in the FRBCAT with various observation frequency bands from the different radio telescopes. Although FRBCAT creates opportunities for us to pursue the matter of FRBs from a variety of frequency bands, the difficulties for statistical study are also confronted, such as the calibration of FRB data from the different telescopes and the uncertain spectral index between the diverse observational frequency bands (Cui et al, 2021a). Nowadays, after the CHIME/FRB Catalog 1 became available, the above dilemma is alleviated because data are only from the CHIME telescope at 400-800MHz (The CHIME/FRB Collaboration et al, 2021a), and the amount of data has also increased significantly, 535 FRB data from 492 sources, in which 462 apparent non-repeaters (hereafter, referred to as non-repeaters) are newly observed (The CHIME/FRB Collaboration et al, 2021a).

The CHIME/FRB collaborations have made many statistical analyses using the new database (The CHIME/FRB Collaboration et al, 2021a; Rafiei-Ravandi et al, 2021; Chawla et al, 2021), and they found that the differences between the repeaters and non-repeaters exist(The CHIME/FRB Collaboration et al, 2021a). Their conclusions further hint that the two groups of FRBs may originate from various paths, or they are likely to come from the same origin but different environments and conditions. However, the FRB luminosity has not been discussed, perhaps because the source distance is hard to determine without localization. In the former studies, luminosity function and distribution of FRBs have been discussed, and many of them are impressive and enlightening (Kumar et al, 2017; Li et al, 2017; Luo et al, 2018; Hashimoto et al, 2020; Luo et al, 2020a). Among the evidence and results, the luminosity distribution of FRBs is likely preferred to follow a power-law form or Schechter function as a whole (Li et al, 2017; Luo et al, 2018; Lu and Piro, 2019; Luo et al, 2020a; Hashimoto et al, 2022), but this is still an open question because there exist a possibility of lognormal distribution (Cui et al, 2021a). Moreover, Li et al (2021b) recently found that the burst energy distribution of a repeating FRB 121102 is not a single power-law but a bimodal distribution, which may contain a lognormal component. Besides these, whether the repeaters and non-repeaters share the same origin or physical properties is also a controversial issue(Connor, 2019; Caleb et al, 2019). Some statistical analyses suggested

[1] https://www.chime-frb.ca/home
[2] https://www.frbcat.org/

that the different distributions for repeating and non-repeating FRBs may imply multiple origins or physical processes of FRBs (Palaniswamy et al, 2018; Petroff et al, 2019; Fonseca et al, 2020; Cui et al, 2021b; The CHIME/FRB Collaboration et al, 2021a), while others believed that the difference is not so obvious or caused by the selection effects (Connor et al, 2020; Gardenier et al, 2021). Therefore, according to these unsettle questions (Kulkarni et al, 2014; Petroff et al, 2019; Cordes and Chatterjee, 2019), by means of the new CHIME database, the statistical explorations with various physical parameters between repeaters and non-repeaters can go ahead.

For the study of FRB luminosity, the distance estimation is a key step, where the Macquart relation between the dispersion measure and redshift (DM-z) (Macquart et al, 2020) is most useful, which is acquired by the 8 localized FRBs. Here, as the first step, to test the validity of the Macquart relation with the updated 18 localized FRBs, by adding the 10 new ones (Heintz et al, 2020)[3], we showed that the Macquart relation is still applicable (details in Appendix A). Therefore, we employed the Macquart DM-z relation and analyzed the new CHIME data to estimate the FRB luminosity, processing the statistics that include the fittings, Kolmogorov-Smirnov (K-S) test, and Mann-Whitney-Wilcoxon (M-W-W) test (Ivezić et al, 2019; Yang et al, 2019; Cui et al, 2021b).

The structure of our paper is organized as follows. In Section 2, we describe the data selection and luminosity estimation. In Section 3, the FRB luminosity distribution is fitted by the different types of functions, and the results of statistical tests are given. In Section 4, we discuss the error of Macquart DM-z relation, the applicability of lognormal distribution, and the implications of statistical results. Finally, a brief summary is exhibited at the end of the paper.

2 Data selection and estimation

In this section, we elaborate on the data selection of CHIME/FRB Catalog 1 and the estimation of FRB distance, based on which the FRB luminosity is obtained.

2.1 Data selection

Our data are taken from the first release of CHIME/FRB Catalog 1 (The CHIME/FRB Collaboration et al, 2021a) and its website[4]. This catalog contains 474 non-repeaters and 18 repeaters, of which 462 non-repeaters are published for the first time. Due to some reasons, such as data processing methods, instrument responses, and selection functions, the distributions between low DM (ranges in $100-500\,\mathrm{pc\,cm^{-3}}$) and high DM ($\mathrm{DM} > 500\,\mathrm{pc\,cm^{-3}}$) data are different, where DM is the data that removes the Milky Way galaxy contribution (The CHIME/FRB Collaboration et al, 2021a). Therefore, 226 non-repeaters with low DM are selected in our sample, as well as 10 repeaters

[3] http://frbhosts.org/

[4] https://www.chime-frb.ca/home

at low DM. However, the direct distance data have not been given for all sources. If we assume that the Macquart relation (Macquart et al, 2020) of DM-z correlation is correct, we can derive an empirical formula between DM and redshift (DM-z) to roughly estimate the FRB distance. In addition, we also re-examine the Macquart DM-z relation by the latest updated 18 localized FRBs and find that it still follows the previous results, the detail of which is shown in Appendix A.

2.2 FRB Luminosity estimation

We employed the Macquart relation to estimate the distance of FRB, so the first step is to clarify the DM we used. FRB's DM is consist of 4 parts (Cordes and Chatterjee, 2019), originating from the Milky Way galaxy ($\mathrm{DM_{MW}}$), intergalactic medium in cosmic distance ($\mathrm{DM_{IGM}}$), host galaxy ($\mathrm{DM_{host}}$) and surrounding medium ($\mathrm{DM_{sur}}$), respectively. Because only 19 FRBs were localized, we know little information about other host galaxies and their $\mathrm{DM_{excess}}$ ($\mathrm{DM_{IGM}}$, $\mathrm{DM_{host}}$, and $\mathrm{DM_{sur}}$), where $\mathrm{DM_{excess}}$ is used to estimate the upper limit of redshift and distance and $\mathrm{DM_{MW}}$ is subtracted according to YMW model (Yao et al, 2017) but not NE2001 (Cordes and Lazio, 2002).

By using the basic knowledge of distance measures in cosmology (Hogg, 1999), the proper distance (d_p) can be roughly estimated as $d_p = zc/H_0$, where c is speed of light and H_0 is Hubble constant cited from Planck Collaboration et al (2016) and Macquart et al (2020) ($H_0 = 67.74\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). Based on the simplest assumption of a flat universe ($\Omega_k = 0$) and the definition of comoving distance (d_c), the luminosity distance (d_L) is written as $d_L = (1+z)d_c = (1+z)d_p/(1+z) = d_p$. Meanwhile, the data of Catalog 1 are only from CHIME at the frequency band of 400-800 MHz, so we do not need to consider the impact of the different telescope calibrations on the data. Thus, combined with the FRB flux (S), the upper limit of luminosity of non-repeaters can be calculated as $L \sim S d_L^2/(1+z)$. For the 18 repeaters, we also estimated their distances by the above method, and mean values of multiple observations are taken to represent the flux of this source.

3 Analysis and results

In our former work about the luminosity distribution of FRBs, we elucidated that the lognormal distribution is better than the power-law type based on the FRB data by CHIME and other telescopes (Cui et al, 2021a). However, our conclusion was weakened due to the small amount of data and the difficulty of calibrating between the different telescopes. Nowadays, thanks to the CHIME Catalog 1, we can employ sufficient and more uniform data to do the further statistical tests, where the 226 non-repeaters mentioned above are applied and the histogram of their luminosity is plotted in Figure 1.

To start our statistics, the test criteria need to be briefly introduced. The test results are represented by the parameters of coefficient of determination (R^2) and p-values (p_{ks} & p_{mww}), and the procedures are as follows.

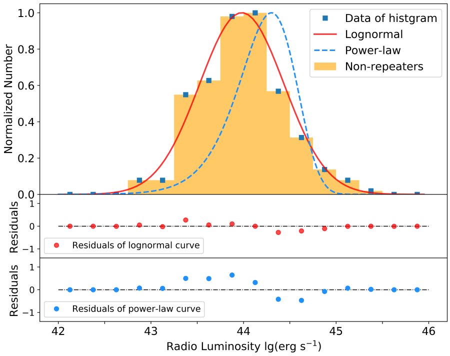

Fig. 1 Upper panel: normalized histogram and different fitted curves of non-repeaters at low dispersion measure (DM) from CHIME/FRB Catalog 1. The solid line is the curve of lognormal form and the dashed line is the curve of power-law type. Middle and bottom panels are the residuals for the lognormal and power-law curve, shown as solid points, where the dash-dotted lines refer to the cases of residual = 0.

Table 1 Statistical test results of different luminosity distribution for non-repeaters at low DM

Different types	Goodness of fit	K-S test	M-W-W test
Lognormal	0.99996	0.735	0.914
Power-law	0.243	2.93×10^{-4}	2.57×10^{-4}

- The closer R^2 is to 1, the better the fit. On the contrary, the fit is worse.
- The lower the p-value, the greater the difference from the null hypothesis that two samples have the same distribution. If the p-value is less than 0.05, it indicates that this test rejects the null hypothesis at a 5% significance level.

Then, we use the lognormal and power-law types to fit the luminosity distribution (in Figure 1) and give the goodness of fit. To avoid deviations caused by different coefficients, we normalized the data and fitted curves and performed statistical analysis on them. From Figure 1, we can see that lognormal curve is closer to the data histogram comparing with power-law curve, and the fitting residuals of lognormal are also smaller than that of power-law, where power-law form is mentioned as Schechter function (Luo et al, 2018). From Table 1, the goodness of fit of lognormal ($R^2_{log} = 0.99996$) is much higher than that of power-law ($R^2_{power} = 0.243$). Moreover, we do the further tests on the lognormal property, by utilizing K-S ($p_{ks} = 0.735$) and M-W-W ($p_{mww} = 0.914$) tests. It should be reminded that we use two test methods, not only for multiple verification, but also because K-S test may have a large error when the sample size is less than 10 (Cui et al, 2021b). Therefore, from the distribution pattern and the above statistical test results, we can initially explain that the lognormal distribution type is significantly better than power-law.

However, we noticed that the above analysis is based on the strict Macquart relation between DM and z. Considering that this relation is based on broad

Table 2 Statistical test results of luminosity distribution with various error shapes and error percentages

Statistical tests	Error shapes	Error percentages									
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
K-S test	Uniform	0.836	0.853	0.824	0.809	0.822	0.819	0.777	0.600	0.321	0.0230
	Normal	0.829	0.807	0.726	0.377	0.249	0.273	0.113	0.127	0.104	0.118
M-W-W test	Uniform	0.786	0.790	0.803	0.799	0.820	0.824	0.817	0.746	0.558	0.199
	Normal	0.786	0.809	0.797	0.597	0.456	0.467	0.347	0.351	0.336	0.342

scattered data points, DM and z relation is not an exactly proportional one-to-one correspondence (Luo et al, 2020a; James et al, 2022). So, we introduce various uncertainties to the DM-z transition, which is from 10% to 100% with a 10% interval in the uniform and normal error pattern, respectively. Specifically, error pattern means that the transition error of DM-z may belong to a particular distribution (uniform or normal), and its statistical characteristics (mean, upper and lower limits for uniform distribution, and mean and variance for normal distribution) are affected by error percentage (10%-100%). Therefore, for each error percentage and error pattern, we perform the Monte Carlo sampling 300 times based on two assumptions: the first is that the probability and shape of error in each data set is the same in one sampling; secondly, the sampling range for each data set depends on its own characteristics. For example, for the data with z = 0.5 and a 20% normal error shape, we take 300 times sampling within normal distribution with a mean of 0.5 and a variance of 0.1. It should be noted that for the situation of large errors like 100%, values of 0 may occur during the sampling process, for which we only use values greater than 0 for analysis. Then, finding the sample data with the maximum (z-max) and minimum (z-min) deviations in each group, we draw them in Figure 2 (uniform) and Figure 3 (normal), and plotting the fitting curve in Figure 1 in each sub-figure. Meanwhile, K-S and M-W-W tests are applied for each z-max group. Nevertheless, in fact, this only performs statistical tests on one set of data, which may cause fluctuations. Thus, to eliminate the randomness of sampling, we do a 100 times loop for the above sampling, and take the mean value of p_{ks} and p_{mww} to represent the test results under the corresponding error percentages and patterns, which is listed in Table 2.

Next, we analyze the data of repeaters and non-repeaters. Because the luminosity distribution of repeaters had been discussed in our previous work and it also showed the lognormal (Cui et al, 2021a), we will not make the redundant tests of the luminosity distribution for the repeaters here. But, it is necessary to compare the distributions of repeaters and non-repeaters again, by considering that there were only 12 non-repeaters in the comparison of the previous work. Therefore, we compare the two samples of repeaters (10) and non-repeaters (226) at low DM in the aspect of luminosity, the distributions of which are plotted in Figure 4, and we employ the K-S and M-W-W tests on these two samples. The results are obtained as $p_{ks} = 0.0415$ and p_{mww}

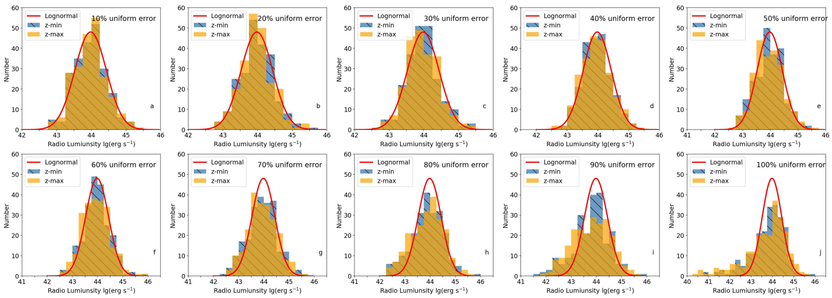

Fig. 2 Luminosity histogram of non-repeaters at low dispersion measure (DM) in uniform error shape with changing error percentages from 10% to 100%, from sub-figure a to sub-figure j. In each sub-figure, the cross-hatched histogram is the maximum deviation and the empty one means the minimum deviation of 300 times sampling in the corresponding error percentage. The line represents the best fitting curve without considering the error of the Macquart relation, which is an unnormalized fitting curve in Figure 1.

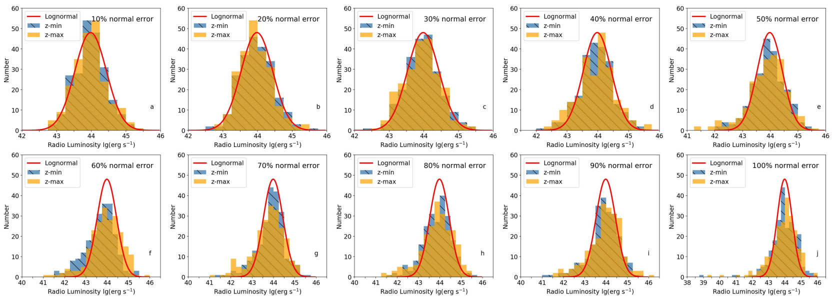

Fig. 3 Luminosity histogram of non-repeaters at low dispersion measure (DM) in normal error shape with changing error percentages from 10% to 100%, from sub-figure a to sub-figure j. Other annotations are consistent with those in Figure 2.

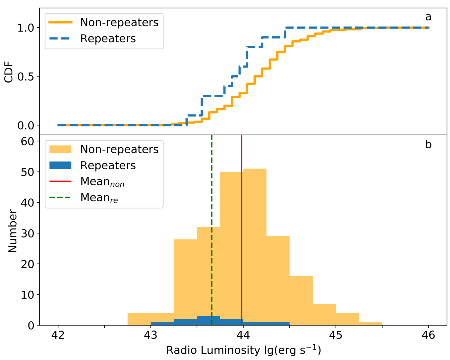

Fig. 4 The distinction between the repeaters and non-repeaters at low dispersion measure (DM) in the aspect of luminosity. The top panel (sub-figure a) is the CDF of repeaters and non-repeaters for luminosity. The dashed (solid) line is for repeaters (non-repeaters). The bottom panel (sub-figure b) is the histogram of luminosity for two samples. The cross-hatched (empty) histogram means the repeaters (non-repeaters). The dashed (solid) line represents the mean value of repeaters (non-repeaters).

= 0.0228, indicating that the two samples may follow the different statistical distributions. These results infer that, although their distribution types are the same, the specific statistical characteristics are different.

4 Discussions and conclusions

Three aspects will be discussed in this section: the applicability of the lognormal for FRB luminosity, the magnetar origin for FRBs, and the difference between the repeaters and non-repeaters. To begin with, we will discuss whether the lognormal distribution will be varied as the error percentage of DM-z relation changes. Then, we discuss what kinds of magnetars can produce the FRB luminosity as obtained, and the models for the repeaters and non-repeaters.

4.1 Applicability of the lognormal distribution

Because our study on the FRB luminosity depends on the distance estimation by the Macquart DM-z relation, which needs further discussions as below. To verify the Macquart relation, we firstly use the new data of 18 localized FRBs to confirm its validity as previously declaimed (as shown in Figure 5 in Appendix A). We obtain that the slope (k) by using a linear function for fitting ($k_{18} \sim 1028$) is almost parallel with the value of Macquart relation ($k_m \sim 973$), and the difference between the two slops is no more than 6%. Under the constraints of 10 new data of localized FRBs, the Macquart relation does not change significantly, and the further analysis is listed in Appendix. Therefore it is reasonable that we employ this DM-z relation to estimate the distance to calculate the FRB luminosity. Then, the approximated isotropic luminosity data of FRBs based on the CHIME/FRB Catalog 1 are acquired under the Macquart relation, which follows the lognormal distribution and rejects the power-law type.

However, considering that the DM-z relation is not a strict one-to-one conversion from DM to z (distance), the lognormal distribution of FRB luminosity will be deformed with the increase of error for DM-z correlation. Here, with the different error shapes (uniform and normal type) and error percentages (from 10% to 100%), the variations of the lognormal characteristics are represented by statistical test results (p_{ks} and p_{mww}), which means that the lognormal distribution may be constrained with a certain scope of application. According to Table 2, for the different error percentages, the lognormal characteristics are gradually decreasing under K-S and M-W-W test results. Although the vast majority of p-values are greater than 0.05, this clear downward trend indicates a weakening of lognormal feature. Meanwhile, with an error of 100%, the p-values of statistical tests start to appear less than 0.05, such as p_{ks} in uniform error, which means that the lognormal feature is broken. Thus, it is inferred that when the estimation error of the Macquart relation between DM and z is less than 100%, the lognormal luminosity distribution is credible. On the contrary, the lognormal feature is not obvious when the error is higher than

100%. Furthermore, we also analyze the data of high and low DM in Appendix B, and the results are slightly different, but still consistent with lognormal distribution.

It should be clarified that the errors we are discussing here do not come from a particular uncertainty, but representing all possible aspects in DM-z transition. This is intended to simulate and test whether the form of luminosity distribution changes when uncertainty is introduced, rather than to describe and discuss the type and cause of specific error. Indeed, the selective effect and the observational bias may significantly affect DM-z conversion, so James et al (2022) gave the detailed analysis for possible errors and concluded that works may produce erroneous results when assuming a 1-1 DM-z relation, which is consistent with our original intention to add errors in DM-z conversion. Meanwhile, since our curve fitting is only for the situation that the error is not considered, the fitting result may have a slight change after the error is introduced, but this will not affect our final conclusion, because the statistical test values are given for the different errors.

4.2 Magnetar origin of FRBs

Next, we discuss the upper limit of luminosity that we obtained in Figure 1. As concluded in our former work (Cui et al, 2021a) and combined with new CHIME data, the lognormal distribution is more supportive of the magnetar origin models (Popov and Postnov, 2010; Lyutikov and Popov, 2020), and it is also valid in terms of the magnitude of the luminosity. In particular, for 226 non-repeaters, the maximum luminosity (L_{max}) is about $2.86 \times 10^{45}\,\mathrm{erg\,s^{-1}}$ and the minimum luminosity (L_{min}) is about $6.84\times10^{42}\,\mathrm{erg\,s^{-1}}$ with the mean value of $9.58\times10^{43}\,\mathrm{erg\,s^{-1}}$. Some giant flares from soft-γ-ray repeaters (SGRs) that are about $10^{44}\,\mathrm{erg\,s^{-1}}$ in hard X-ray or soft γ-ray band (Mazets et al, 1979; Hurley et al, 1999; Mereghetti et al, 2005). If we consider a relatively high radio efficiency of 0.1 between the radio and X-ray luminosity, then the above SGR luminosity may conform to the FRBs' luminosity. However, if the general radio emission efficiency is about 10^{-5}, like SGR 1935+2154 (Bochenek et al, 2020), then the radio luminosity of SGR will not meet the above FRBs. Only the rare huge-giant flare can satisfy with the obtained FRB luminosity (Lyutikov, 2017), like the spike luminosity of about $10^{47}\,\mathrm{erg\,s^{-1}}$ in the X-ray band (Hurley et al, 2005; Palmer et al, 2005), or the newborn millisecond magnetars may produce such huge-giant flares that have not been observed.

However, for the L_{max} of FRBs being much higher than the inferred radio luminosity of the giant flares of SGRs as observed, it may be necessary to consider that the special magnetars have the super-strong magnetic fields (Beloborodov, 2017), higher than the known values of $10^{15}\,\mathrm{G}$ (Duncan and Thompson, 1992; Kaspi and Beloborodov, 2017). If their magnetic fields increase by half or one order of magnitude to $10^{16}\,\mathrm{G}$, the total released magnetic energy will increase by one or two orders of magnitude, as $E_{tot} \sim B^2V/8\pi \sim 10^{49}\,\mathrm{erg}$, where $B \sim 10^{16}\,\mathrm{G}$ is the surface magnetic field of a young magnetar and $V \sim 10^{18} cm^3$ is the volume of the magnetar. If we assume the radio emission efficiency to be about 10^{-4} and lasting time of FRBs to be 10 milliseconds, then the corresponding FRB luminosity of non-repeater will rise to $10^{47}\,\mathrm{erg\,s^{-1}}$. Therefore, this indicates that the cosmic FRBs are likely to come from the rare and violent bursts of magnetars.

4.3 Difference of repeaters and non-repeaters

The possible distinction between the repeaters and non-repeaters is briefly discussed in this subsection. Although the luminosity distribution of 18 repeaters is also lognormal (Cui et al, 2021a), the two groups have different statistical distributions. The average luminosity of repeaters ($4.56\times10^{43}\,\mathrm{erg\,s^{-1}}$) is about an half lower than that of non-repeaters ($9.58\times10^{43}\,\mathrm{erg\,s^{-1}}$). This implies that they may come from a similar origin but different environments or emission mechanisms, such as the magnetars with the mediate magnetic field strengths or special structures. For example, the magnetic field strength of repeater source is about $10^{14-15}\,\mathrm{G}$, while that of non-repeater may be higher than $10^{15}\,\mathrm{G}$. In terms of the FRB origin models, there are two promising candidate forms: violent outburst from magnetar and supergiant pulse from strong magnetic neutron star (Popov et al, 2018; Katz, 2020; Zhang, 2020). Specifically, the huge-giant flares from ultra-strong magnetar ($\sim 10^{16}\,\mathrm{G}$) (Lyubarsky, 2014; Murase et al, 2016; Beloborodov, 2017) may be one of the explanations for a single burst of non-repeaters, and extremely high luminosity ($\sim 10^{47}\,\mathrm{erg\,s^{-1}}$) could lead to the long burst interval that it is considered as a non-repeater. On the other aspect, the supergiant pulses from the extragalactic neutron stars (Cordes and Wasserman, 2016; Connor et al, 2016) may be a good description for repeaters.

In the end, we need to clarify that the luminosity of two samples may have an overlap part, which means that some non-repeaters may be repeated in the future, like FRB 171019 (Kumar et al, 2019). In other words, the merger of the binary system (Totani, 2013; Kashiyama et al, 2013; Mingarelli et al, 2015) and catastrophic collision events (Geng and Huang, 2015; Dai et al, 2016) may also be mixed in the non-repeater sample. However, the proportion of these one-time collision events should be a small part, because the luminosity distribution of non-repeaters does not have an obvious bimodal distribution. Therefore, the non-repeater samples can also be divided into two groups: the true non-repeaters and repeaters as a single observed burst. Finally, because of fewer sample data of only 18 repeaters, its statistical conclusion might be tentative. Thus we look forward to having more such data to uncover the mysteries of FRBs.

A brief summary of conclusions:

- We added the latest 10 localized FRBs to reconfirm the Macquart relation, indicating that this relation is still credible for the known 18 localized FRBs.
- The luminosity of repeaters and non-repeaters are calculated based on the distance estimated by the Macquart relation, and their distribution conforms

with the lognormal with the different mean values and derivations. However, the lognormal features decrease as the transition error of DM-z increases until the error reaches 100%, at where the lognormal features are destroyed.
- These implies that the two samples possibly come from similar origins, such as magnetar or strong magnetic NS.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (Grant No. 11988101, No. U1938117, No. U1731238, No. 11703003 and No. 11725313), the International Partnership Program of Chinese Academy of Sciences grant No. 114A11KYSB20160008, the National Key R&D Program of China No. 2016YFA0400702, and the Guizhou Provincial Science and Technology Foundation (Grant No. [2020]1Y019). The data underlying this article are available in the references below: (1) The data of repeating and non-repeaters are taken from the database of CHIME/FRB Catalog 1, available at https://www.chime-frb.ca/home. (2) The information of localized FRB is provided at the web http://frbhosts.org/

Appendix A: Verification of the Macquart relation with updated 18 localized FRBs

When the Macquart relation was given, only 8 localized FRBs were considered. Now, we add the newly localized 10 FRBs, and a total of 18 data points are taken into account to verify the Macquart relation. Since the M81 is too close to us (Bhardwaj et al, 2021), FRB 20200120E is not listed in the above 18 data. The fitted line of 18 data is given, with the goodness of fit as 0.75. As shown in Figure 5, our fitted line (solid) is almost parallel to that of the Macqurat relation (dashed), and the deviation of two slopes is less than 6%. This indicates that the DM-z relation is still available, at least for the case that z is less than 0.7. While the obvious difference between the two lines is reflected as a fact that our fitting has an intercept value of 84.43 $\mathrm{pc\,cm^{-3}}$ with the vertical axis. A possible reason for this gap is that the different DM data have been used. Our $\mathrm{DM_{excess}}$ contain the $\mathrm{DM_{host}}$ and $\mathrm{DM_{sur}}$, but the $\mathrm{DM_{cosmic}}$ in the Macquart relation does not. Therefore, the gap value of 84.43 $\mathrm{pc\,cm^{-3}}$ may infer the DM in the host galaxy or surrounding medium or both of them.

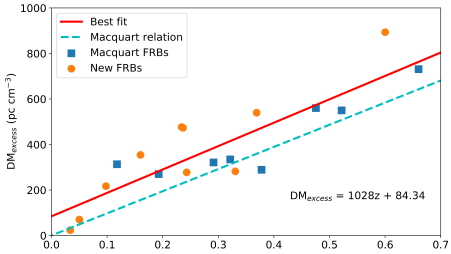

Fig. 5 Diagram of dispersion measure (DM) and redshift (z). The solid line represents the best fit curve of 18 localized FRBs, and the dashed line stands for the Macquart relation. The squares represent 8 localized FRBs given by Macquart et al (2020), and the 10 circles are the newly added data.

Appendix B: Analysis of both high and low DM data

Under our data selection, we only analyze the repeaters and non-repeaters at low DM, so we discuss all data here, including FRBs at both high and low DM. The goodness of fit, K-S and M-W-W tests are also applied on these data, and the results are shown in Table 3, which further support the lognormal distribution of luminosity for non-repeaters. Meanwhile, the same method is used as the previous, and we plotted them in Figure 6 with mean values of repeaters ($5.04 \times 10^{43}\, erg\, s^{-1}$) and non-repeaters ($1.86 \times 10^{44}\, erg\, s^{-1}$). Although the repeaters and non-repeaters still show the different distributions ($p_{ks} = 3.88 \times 10^{-3}$ and $p_{mww} = 2.21 \times 10^{-4}$) like in the case of low DM selection, the mean values of all data are inconsistent with the data at low DM, indicating that the high and low DM may indeed be different. Furthermore, the maximum and minimum luminosity of them is $7.57 \times 10^{45}\,\mathrm{erg\,s^{-1}}$ and $3.62 \times 10^{42}\,\mathrm{erg\,s^{-1}}$, respectively, which has a wider distribution range than the non-repeaters at low DM. Therefore, these imply that the reasons for these differences are possibly due to the observational effects, data processing methods, or even their intrinsic physical properties, and we need further study to figure out the puzzles.

Table 3 Statistical test results of different luminosity distribution for all non-repeaters

Different types	Goodness of fit	K-S test	M-W-W test
Lognormal	0.963	0.918	0.900
Power-law	5.96×10^{-4}	2.22×10^{-16}	1.78×10^{-10}

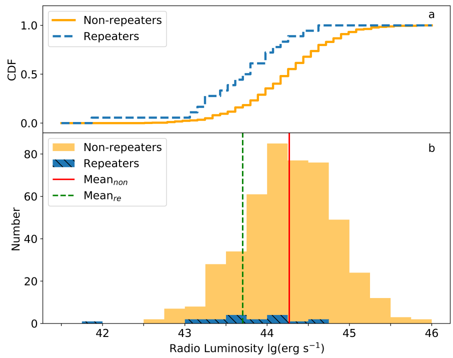

Fig. 6 The distinction for all repeaters and non-repeaters (both low and high dispersion measure (DM)) in the aspect of luminosity. The top panel (sub-figure a) is the CDF of repeaters and non-repeaters for luminosity. The dashed (solid) line is for repeaters (non-repeaters). The bottom panel (sub-figure b) is the histogram of luminosity for two samples. The cross-hatched (empty) histogram means the repeaters (non-repeaters). The dashed (solid) line represents the mean value of repeaters (non-repeaters).

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Statements & Declarations

Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 11988101, No. U1938117, No. U1731238, No. 11703003 and No. 11725313), the International Partnership Program of Chinese Academy of Sciences grant No. 114A11KYSB20160008, the National Key R&D Program of China No. 2016YFA0400702, and the Guizhou Provincial Science and Technology Foundation (Grant No. [2020]1Y019).

Data availability

The dataset of repeaters and non-repeaters is available in the CHIME/FRB Catalog 1 repository, https://www.chime-frb.ca/home. The dataset of localized FRBs is available in the FRB HOST DATABASE, http://frbhosts.org/.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Xianghan Cui and Chengmin Zhang wrote the main manuscript text, Di Li and Jianwei Zhang provied analytical methods, Di Li, Bo Peng, Weiwei Zhu. and Richard Strom illustrated physical properties, Shuangqiang Wang, Na Wang and Qingdong Wu gave suggestions on figures, and Dehua Wang and Yangyi Yan modify the manuscript. All authors participated in the discussion and read the manuscript.