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The prevalence of repeating fast radio bursts

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Fast radio bursts are extragalactic, sub-millisecond radio impulses of unknown origin[1,2]. Their dispersion measures, which quantify the observed frequency-dependent dispersive delays in terms of free-electron column densities, greatly exceed predictions from models[3] of the Milky Way interstellar medium. The excess dispersions are probably accrued as fast radio bursts propagate through their host galaxies, gaseous galactic halos and the intergalactic medium[4,5]. Despite extensive follow-up observations of the published sample of 72 burst sources[6], only two have been observed to repeat[7,8], and it is unknown whether the remainder are truly one-off events. Here I show that the volumetric occurrence rate of the fast radio bursts that have not been observed to repeat thus far probably exceeds the rates of candidate cataclysmic progenitor events, and also probably exceeds the birth rates of candidate compact-object sources. This analysis is based on the high detection rate of bursts with low dispersion measures by the Canadian Hydrogen Intensity Mapping Experiment (CHIME)[9]. Within the existing suite of astrophysical scenarios for fast radio burst progenitors, I conclude that most observed cases must originate from sources that emit several bursts over their lifetimes.

Thirteen fast radio bursts (FRBs) were published by the CHIME collaboration, including one repeating source (FRB 180814.J0422 + 73) that I exclude from my analysis[8,9] (see Methods). These events were detected during a pre-commissioning phase when the instrument was not operating with its full sensitivity and field of view. The survey was conducted over less than 7.82×10^{-5} sky-years, implying an all-sky FRB rate floor of 300 per day in the 400–800 MHz CHIME frequency band. Despite the systematic uncertainties, this is an order of magnitude greater than the rate of bright FRBs detected with the Australian Square Kilometre Array Pathfinder (ASKAP)[10]. Additionally, although the ASKAP FRBs typically have lower excess dispersion measures than FRBs detected with the more sensitive Parkes telescope, CHIME has a detection rate more than ten times higher than ASKAP's at low excess dispersion measures (Fig. 1). This motivated the present analysis of the volumetric occurrence rate of FRBs.

The paucity of direct distance measurements for FRBs, based for example on observations of FRB host galaxies, has meant that FRB volumetric-rate estimates have relied on ascribing dominant fractions of the excess dispersion measures to the intergalactic medium[1,11]. I define the extragalactic dispersion measure, DM_X, as the difference between FRB dispersion measures and predictions from models[3] of the Milky Way interstellar medium (DM_{MW}). If FRB DM_X values were entirely built up from a homogeneous intergalactic medium comprising all cosmic baryons, the DM_X range of the CHIME sample of 79–979 pc cm^{-3} would correspond to a range of comoving distances, d, of 0.34–2.52 gigaparsecs (Gpc)[4]. This assumption, together with a host-galaxy contribution to DM_X of 100 pc cm^{-3}, was previously applied to an early sample of four FRBs from the Parkes telescope to derive a volumetric rate of 2.4×10^4 Gpc^{-3} yr^{-1} (refs [1,11]). Substantial, hard-to-quantify uncertainties affect this estimate, including the sample completeness at different distances, the host-galaxy DM_X contributions and the effects of cosmological evolution in the FRB population.

Here I derive a robust lower limit on the FRB volumetric rate using the CHIME sample of low-DM_X bursts. For each FRB, I consider the following components of DM_X:

$$DM_X = DM - DM_{MW} = DM_{MWhalo} + DM_{IGM} + DM_{host} \quad (1)$$

where DM_{MW} is estimated from the NE2001 model for the Milky Way ionized interstellar medium[3], DM_{MWhalo} arises in the Milky Way hot gaseous halo[5], DM_{IGM} arises in the intergalactic medium[4], and DM_{host} arises in FRB host galaxies. I adopt a relation between DM_{IGM} and cosmological distance that incorporates the primordial helium fraction and an intergalactic medium baryon fraction of 0.84 (ref. [12]), with a normally distributed scatter of 10 pc cm^{-3} (ref. [4]). Recent observations of ultraviolet and X-ray quasar absorption lines associated with the Galactic halo imply the presence of a substantial gas mass at temperatures in the range 10^4–10^7 K, in agreement with observations of other galaxies and cosmological simulations, that contributes between 50–80 pc cm^{-3} out to the Milky Way virial radius[5]. I therefore assume that DM_{MWhalo} can have any value between 50 pc cm^{-3} and the minimum of 80 pc cm^{-3} and ($DM_X - DM_{host}$) with equal probability. I perform the analysis below for different characteristic values of DM_{host}. These features imply a probability distribution, $P(<DM_X|d)$, for an FRB to have an extragalactic dispersion measure that is less than the expectation for a given value of d (see Supplementary Fig. 1).

A comparison of the DM_X distributions of FRB samples from ASKAP and Parkes suggests that ASKAP is increasingly incomplete at higher values of DM_X because of its insensitivity to the faint, high-DM_X FRBs observed by the Parkes telescope[10]. This effect, together with a possible correlation between FRB temporal widths and DM_X (refs [2,9]), and additional unknown systematics in the CHIME observations[9], strongly suggests that CHIME is also increasingly incomplete at higher values of DM_X. I mitigate this unknown incompleteness by deriving a lower limit on the FRB rate, R, within a limited volume bounded at $d = d_{limit}$ that contains the lowest-DM_X CHIME FRBs. I choose a d_{limit} such that $P(<DM_X|d)$ is essentially unity for the lowest-DM_X FRB (180729.J1316 + 55, $DM_X = 78.610$ pc cm^{-3}), and 0.95 for the FRB with the second-lowest DM_X (FRB 180810.J1159 + 83, $DM_X = 122.134$ pc cm^{-3}); for no DM_{host} contribution, $d_{limit} = 426$ megaparsecs (Mpc). I also consider the case where $P(<DM_X|d)$ is essentially unity for the two abovementioned FRBs, and 0.95 for the event with the third-lowest DM_X (FRB 180814.J1554 + 74; $DM_X = 197.32$ pc cm^{-3}; $d_{limit} = 739$ Mpc). When $P(<DM_x|d) \approx 1$, the probability of having observed the FRB within a volume bounded by d is likely also to be approximately unity.

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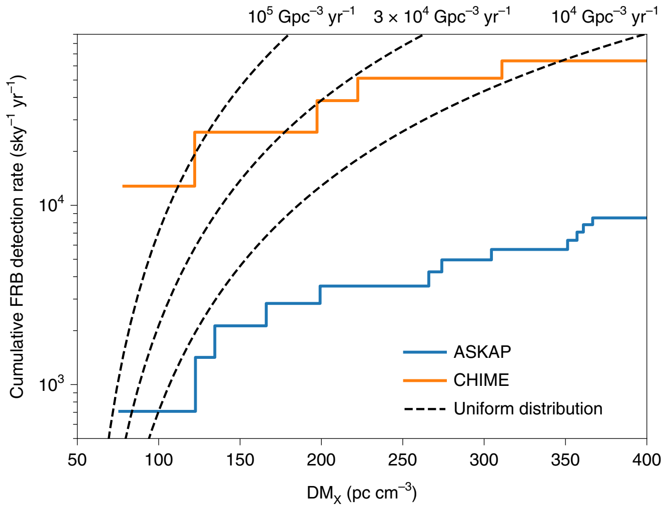

Fig. 1 | Comparison of the detection rates of ASKAP and CHIME for FRBs within different extragalactic dispersion measures. The detection rates were calculated assuming survey extents of 1.41×10^{-3} sky-years for ASKAP[10] and 7.82×10^{-5} sky-years for CHIME[9]. At each extragalactic dispersion measure (DM_X), the detection rate was calculated by dividing the number of FRBs at or below that DM_X by the survey extent. The dashed lines show curves of predicted cumulative FRB detection rates assuming various comoving volumetric rates (noted at the top of the figure) with no observational incompleteness, $DM_{MWhalo} = 50\,pc\,cm^{-3}$, and $DM_{host} = 0\,pc\,cm^{-3}$ (see Methods).

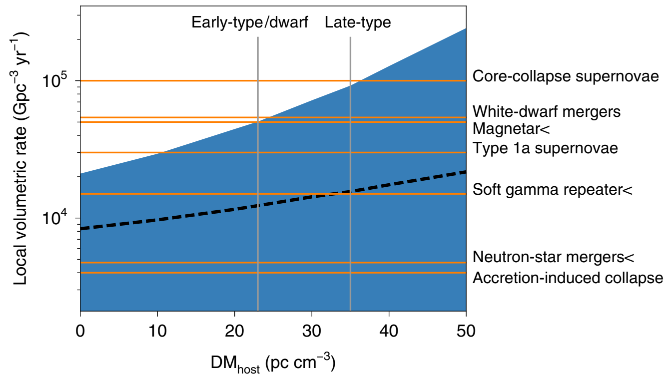

Fig. 2 | Lower limits on the FRB volumetric rate for different characteristic host-galaxy dispersion measures. Rates within the blue-shaded region are excluded with >90% confidence given a d_{limit} corresponding to two CHIME FRBs, and the black dashed line indicates the 90%-confidence limit given a d_{limit} corresponding to three CHIME FRBs. The limits were calculated using FRBs observed during the CHIME pre-commissioning phase, with a detection threshold of approximately 1 Jy ms for millisecond-duration FRBs[9], and assuming Poisson statistics for the occurrence of so far non-repeating FRBs. The horizontal orange lines indicate estimates of the occurrence rates of candidate cataclysmic FRB progenitors, and the birth rates of candidate compact-object FRB sources. The former includes mergers of white dwarfs[23], of which type Ia supernovae may be a special case[33], mergers of neutron stars (a recent observational upper limit is indicated)[21], and accretion-induced collapse of white dwarfs[25]. The latter includes neutron stars produced in core-collapse supernovae, and neutron stars born as magnetars (an upper limit on the highly uncertain rate is shown)[28] and through the white-dwarf merger, neutron-star merger and accretion-induced-collapse channels. I also show an upper limit on the rate of soft gamma repeater giant flares[34], which are a popular scenario for FRB production[14]. The vertical grey lines show the characteristic DM_{host} values for orientation-averaged early-type and dwarf galaxies, and for face-on late-type galaxies.

Assuming that the FRBs that have not been observed to repeat thus far are independent events associated with distinct sources, their observed occurrence within the bounded volume can be modelled as a Poisson process. Lower limits on R can then be derived from the number of observed events using the Poisson probability mass function (see Methods)[13]. For the two cases of d_{limit} described above, I assume that two and three FRBs were observed respectively, and calculate the corresponding conservative 90%-confidence lower limits on R. Direct statistical inference on R cannot be performed without specifying a model for the unknown incompleteness of the CHIME observations. Besides this incompleteness, the lower limits quoted below are conservative because they do not account for possible angular beaming of FRBs and cosmological time-dilation.

I evaluate d_{limit} and the 90%-confidence lower limit on R for different values of DM_{host}, and the results are shown in Fig. 2. The lower limit on R is less constraining for d_{limit} corresponding to three observed FRBs than for d_{limit} corresponding to two observed FRBs. The lower limits on R decrease as d_{limit} is increased to include more CHIME FRBs, which may indicate increasing incompleteness at higher values of DM_X. Below, I quote lower limits on R for d_{limit} corresponding to two observed FRBs. For no assumed DM_{host}, $R > 2.1 \times 10^4\,Gpc^{-3}\,yr^{-1}$, and for $DM_{host} = 50\,pc\,cm^{-3}$, $R > 2.4 \times 10^5\,Gpc^{-3}\,yr^{-1}$. Despite these lower limits being conservative, they are comparable to the estimate of $R \approx 2.4 \times 10^4\,Gpc^{-3}\,yr^{-1}$ from the initial sample of four Parkes FRBs where $DM_{host} = 100\,pc\,cm^{-3}$ was assumed[1,11]. This may be explained by the uncertainties noted above for the latter observations, such as incompleteness in the Parkes sample given the large d_{limit} that was adopted. I note that such a large DM_{host} would not be compatible with the lowest-DM_X CHIME FRBs.

The FRB rates derived herein can be compared with predictions for non-repeating FRB progenitors, and with the estimated birth rates of FRB sources (see Fig. 2). All astrophysical FRB progenitors (excluding those attributed to new physics) are expected to be contained within galaxies, in many cases in regions with atypically dense interstellar medium[14]. Simulations of the DM_{host} values corresponding to typical locations within inclination-averaged early-type and dwarf galaxies suggest $DM_{host} = 23\,pc\,cm^{-3}$, and $DM_{host} = 35\,pc\,cm^{-3}$ is likely to be characteristic of typical locations within face-on late-type galaxies[15,16]. Substantially larger values of DM_{host} of a few hundred parsecs per cubic centimetre were recently inferred for the ASKAP FRB sample on the basis of a comparison between FRB dispersion measures from ASKAP, Parkes and CHIME, and a tentative correlation between the ASKAP FRB sky-locations and catalogues of nearby galaxies[17].

Models for non-repeating FRB progenitor events rely on the destruction of highly magnetized white dwarfs or neutron stars. These events are, however, probably too rare to produce FRBs at the observed rate. For example, FRBs may be produced upon the merger of two white dwarfs[18], the merger of two neutron stars[19], or the collapse of a neutron star to a black hole[20]. Gravitational-wave observations have demonstrated that neutron-star mergers occur at less than a quarter of the FRB volumetric-rate limit[21]. Binary white dwarfs probably trace stellar mass, with a possible preference for galactic disks, making it unlikely that all white-dwarf mergers are found in under-dense regions of their host galaxies[22], as is required for this FRB progenitor channel[23]. Further, only neutron-star mergers and the accretion-induced collapse of white dwarfs[24,25] can form massive, rotationally supported neutron stars that rapidly collapse to black holes in sufficiently sparse environments for FRB radiation to escape[11].

Predictions for the birth rate of stellar-mass compact objects that can produce FRBs are also inconsistent with the FRB volumetric rate, if FRB sources do not repeat. Core-collapse supernovae (about $10^5\,\mathrm{Gpc^{-3}\,yr^{-1}}$)[26] are probably the most common channel for compact-object production, and are consistent with the FRB volumetric-rate limit for low $\mathrm{DM_{host}}$. However, their young stellar progenitors are usually associated with the star-forming regions of galaxies[27], and their compact-object remnants would need to migrate into less-dense regions and age prior to FRB production to avoid incompatibility with the FRB volumetric rate caused by a high $\mathrm{DM_{host}}$ (ref. [16]). The magnetar birth rate is at most half the core-collapse rate[28], and active magnetars in the Milky Way are found only close to the Galactic plane. Other channels for compact-object production (for example, neutron-star and white-dwarf mergers, and accretion-induced collapse of white dwarfs) have even lower volumetric rates.

If FRBs are associated with stellar-mass compact objects produced through the standard astrophysical channels summarized in Fig. 2, the high FRB volumetric rate implies that the majority of FRB sources repeat. Most FRB progenitor channels require specially configured compact objects, such as young magnetars and neutron stars in unusual environments[14]. The precise repetition rates of individual FRB sources will depend on the birth rates of the specific progenitor objects, and the lifetimes over which FRBs can be emitted. Recent analyses of the population of FRB sources similar to the repeating FRB 121102 suggest that this object is atypical of the population of FRBs that have not thus far been observed to repeat[29,30]. However, for example, even an FRB production rate of about 100 events per Hubble time per source would be sufficient to resolve the present tension with many of the models discussed here. Ongoing observations with CHIME will provide unprecedented sensitivity to the range of possible FRB repetition rates, together with a larger sample of low-$\mathrm{DM_X}$ FRBs to refine the present analysis. The localization of a large sample of FRBs to regions within their host galaxies will enable quantitative tests of population synthesis models for astrophysical FRB progenitors, and estimates of the progenitor ages that will in turn better quantify the expected repeat rates. If the sample completeness can be quantified, FRB distance measurements based on observations of host galaxies will enable a direct measurement of the FRB volumetric rate.

Methods

The choice of the lowest possible d_{limit} values to contain either two or three FRBs does not upwardly bias the lower limit on the FRB rate. I demonstrate this through a simulation. Consider FRBs that are uniformly distributed in space, with a rate of one event per unit time per unit volume. I simulated 10^4 samples of 10^3 events, where in each sample the actual number of events was drawn from a Poisson distribution with a rate parameter of 10^3. I then recorded the distances to the nearest three FRBs in each sample (d_1, d_2 and d_3 respectively). 90%-confidence lower limits on the volumetric rate were calculated as in the main text[13]: $R_1 = 0.105\times[(4/3)\pi d_1^3]^{-1}$, $R_2 = 0.532\times[(4/3)\pi d_2^3]^{-1}$ and $R_3 = 1.102\times[(4/3)\pi d_3^3]^{-1}$ for each sample. Histograms of R_1, R_2 and R_3 are shown in Supplementary Fig. 2, and the 90th percentiles of the samples are indicated. In each case, the 90th percentiles are very close to the true rate of unity. This exercise was also carried out for 10^4 samples of Poisson-distributed events with an expectation of 12, with identical results.

The use of a low d_{limit} is also motivated by the observations. Figure 1 shows the empirical cumulative distributions of FRB $\mathrm{DM_X}$ values from ASKAP and CHIME, quantified as all-sky detection rates using the survey extents. I also show curves of predicted FRB all-sky detection rates assuming various comoving volumetric rates and no observational incompleteness, $\mathrm{DM_{MWhalo}} = 50\,\mathrm{pc\,cm^{-3}}$, $\mathrm{DM_{host}} = 0\,\mathrm{pc\,cm^{-3}}$, and assuming the same relation between dispersion measure and distance (with no scatter) as in the main text. Cosmological time-dilation effects are included. The shallowness of the CHIME (and ASKAP) empirical distribution of $\mathrm{DM_X}$ values in comparison with the predicted curves suggests incompleteness that increases with $\mathrm{DM_X}$. A similar argument was made in ref. [31] (see, for example, their figure 1). This effect is also evidenced by the decrease in the lower limits on the FRB rate, R, for increasing values of d_{limit}. For example, the 90% confidence lower limits on R for d_{limit} corresponding to four and five FRBs are $R > 8.9\times10^3\,\mathrm{Gpc^{-3}\,yr^{-1}}$ and $R > 4.8\times10^3\,\mathrm{Gpc^{-3}\,yr^{-1}}$ respectively, for $\mathrm{DM_{host}} = 0\,\mathrm{pc\,cm^{-3}}$. These arguments only hold as long as $\mathrm{DM_X}$ values are typically dominated by $\mathrm{DM_{IGM}}$. However, if this were not the case, the conclusions reached in the main text would only be strengthened.

The repeating CHIME FRB 180814.J0422 + 73 was not included in the present analysis despite its low $\mathrm{DM_X} = 102.4\,\mathrm{pc\,cm^{-3}}$ (ref. [8]). This is partly because of the evidence that several properties of the first repeating FRB 121102, some of which (for example, the observed repetition, and the burst time-frequency structure) are inconsistent with the population of FRBs that have not been observed to repeat[2,29,30]. Additionally, although the $\mathrm{DM_X}$ of FRB 180814.J0422 + 73 is lower than that of FRB 180810.J1159 + 83, the conclusions reached in the main text are independent of its inclusion in the analysis.

The results presented in the main text are robust to the choice of model for the dispersion measure contribution from the Milky Way ionized interstellar medium ($\mathrm{DM_{MW}}$). For example, if the YMW17[32] model is used instead of the NE2001 model, the lower limit on the FRB rate, R, derived for d_{limit} corresponding to two FRBs and $\mathrm{DM_{host}} = 0\,\mathrm{pc\,cm^{-3}}$ changes from $R > 2.1\times10^4\,\mathrm{Gpc^{-3}\,yr^{-1}}$ to $R > 1.8\times10^4\,\mathrm{Gpc^{-3}\,yr^{-1}}$.

Data Availability

The datasets analysed during the current study are available from the FRB Catalogue: http://frbcat.org/.

Code Availability

Custom code used in this study is available at https://github.com/VR-DSA/frb_rate.

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