Constraining the Fast Radio Burst (FRB) properties using the detections at Parkes, ASKAP and CHIME

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ABSTRACT

We demonstrate how the FRB redshift and fluence distributions from the Parkes, ASKAP and CHIME telescopes can be used together to constrain the properties of the FRB population. Here we consider a simple model where all the FRBs have the same spectral index $\alpha$ and rest frame energy $E$ (specified in a fixed band 2128 MHz to 2848 MHz). We find that the constraints on $(\alpha, E)$ depend on the scattering model for pulse broadening in the inter-galactic medium. For no scattering we find that there is a region of parameter space where the predictions are simultaneously consistent with the FRB redshift and fluence distributions at all three telescopes. The allowed $\alpha$ range is bounded by $-6.0 \leq \alpha \leq -3.6$ and the allowed $E$ range is bounded by $1.79 \times 10^{33} \text{J} \leq E \leq 5.41 \times 10^{33} \text{J}$. Our analysis also rules out an empirical scattering model where the FRB pulse broadening in the IGM is predicted by extrapolating pulse broadening observed for pulsars in the ISM.

Key words: radio continuum: transients, scattering.

1 INTRODUCTION

Fast Radio Bursts (FRBs) are short duration highly energetic dispersed radio pulses first detected at Parkes (Lorimer et al. 2007). FRBs have since been detected at Parkes (Thornton et al. 2013; Champion et al. 2016 and Bhandari & Keane 2017), Arecibo (Spielter et al. 2014 and Patel et al. 2018), GBT (Masui et al. 2015), ASKAP (Bannister et al. 2017; Shannon et al. 2018 and Macquart et al. 2018), UTMOST (Caleb et al. 2017; Farah et al. 2018a; Farah et al. 2018b and Farah et al. 2018c), CHIME (Boyle et al. 2018 and CHIME/FRB collaboration et al. 2019a) and Puschino (Rodin et al. 2018). A total of around 79 FRBs have been made public through an online database\textsuperscript{1}, and of these only 3 FRBs (Spielter et al. 2014; Patel et al. 2018 and CHIME/FRB collaboration et al. 2019b) are found to repeat. The observed dispersion measures (DMs), which are $\sim 5$ to 20 times in excess of the DMs of the Milky Way, suggest that FRBs are extragalactic in origin. A single repeating FRB has been localized to a $z = 0.19$ galaxy (Chatterjee et al. 2017 and Tendulkar et al. 2017). There are no independent redshift measurements for the other FRBs, and the redshifts are inferred from the measured DMs.

Several models have been proposed for the FRB emission mechanism but a clear physical picture is still lacking. For example, it has been proposed that FRBs originate from the merger of compact objects like neutron star and/or white dwarfs. The reader is referred to Platts et al. (2018) for summary of potential FRB models. Several authors have also tried to constrain the FRB source properties without reference to any particular emission mechanism. Macquart et al. (2019) have estimated the mean spectral index of 23 FRBs detected at ASKAP as $\alpha = -1.5_{-0.2}^{+0.2}$ though the estimated values of $\alpha$ vary from +7 to $-7.5$ across the sample. Bhattacharya et al. (2019) have used simulations of the FRB population to estimate that the FRBs detected at Parkes have spectral indices in the range $-3 \leq \alpha \leq -1.5$. It is at present not clear whether the repeating FRBs originate from same kind of sources as the non-repeating ones (Lu et al. 2019). Houben et al. (2019) have proposed a lower limit $\alpha > -1.2 \pm 0.4$ for the spectral index of FRBs based on the fact that the repeating FRB 121102, which was detected at 1.4 GHz, was not detected at 150 MHz. Ravi & Loeb (2018) have modelled the FRB spectrum using a broken power law to explain the dearth of FRB detection at low frequencies.

Here we focus on the non-repeating FRBs detected at Parkes, ASKAP and CHIME i.e. a total 63 FRBs.
reported to date. Of these 28 FRBs have been detected at Parkes (Petroff et al. 2016; Petroff et al. 2017; Keane et al. 2016; Ravi et al. 2016; Bhandari & Keane 2017; Shannon et al. 2017; Price et al. 2018; Oslowski et al. 2018a; Oslowski et al. 2018b; Oslowski et al. 2018c and Bhandari et al. 2018). 23 FRBs have been detected at ASKAP (Bannister et al. 2017; Shannon et al. 2018 and Macquart et al. 2018) and 12 FRBs at CHIME (Boyle et al. 2018 and CHIME/FRB collaboration et al. 2019). These together account for ~80% of the total FRBs for which the data is currently publicly available. The Parkes observations, which are centered at 1352 MHz, have a small field-of-view (~0.6 deg²) and a relatively low limiting fluence 0.5 Jyms for FRB detection. This provide us with a deep FRB sample extending out to a maximum redshift of \( z_{\text{max}} = 2.63 \). In contrast the ASKAP observations, which are centered at a comparable frequency (1296 MHz), have a large field of view (~30 deg²) and a relatively highly limiting fluence of 24.4 Jy ms. These observations provide us with a relatively shallow FRB sample extending to a maximum redshift of \( z_{\text{max}} = 0.92 \). The CHIME observations, which are at a relatively lower frequency (600 MHz), have a large field of view (~250 deg²) and a limiting fluence of 0.64 Jy ms. Like the ASKAP sample, this also does not extend beyond \( z = 1 \) with \( z_{\text{max}} = 0.94 \). It is interesting and worthwhile to consider if we can construct simple models for the FRB population that can simultaneously match this combined data which spans different observing frequencies and redshift ranges. The energy and spectral index range allowed by such models will provide important inputs regarding the physical mechanism for FRBs.

In this Letter we consider a very simple model for the FRB population where all the FRBs have the same energy \( E \) and spectral index \( \alpha \). The FRB event rate per comoving volume is also assumed to be constant across the \( z \) range of our interest. Using the Kolmogorov-Smirnov (KS) test, we determine if the predictions of our simple model are consistent with the redshift and fluence distributions of the FRBs observed at Parkes, ASKAP and CHIME. We use this to constrain the region of parameter space \((E, \alpha)\) which is simultaneously consistent with the observations at these three different telescopes and rule out the remaining parameter space at a high level of significance. In addition to the intrinsic FRB properties, propagation effects can be important in shaping the observed FRB distribution. We have accounted for this by considering two possible scattering models along with the situation where there is no scattering.

2 METHODOLOGY

We model the specific energy \( E_s \) of an FRB in its rest frame as \( E_s = E \phi(\nu) \) where the frequency profile \( \phi(\nu) \) is normalized with \( \int_0^{\nu_b} \phi(\nu) d\nu = 1 \) with \( \nu_b = 2128 \) MHz and \( \nu_b \approx 2848 \) MHz, and \( E \) is the energy emitted in the interval \( \nu_a \) to \( \nu_b \). We refer here to \( E \) as the energy of the FRB. Further, we have assumed a power law \( \phi(\nu) \propto \nu^\alpha \) where \( \alpha \) is the spectral index. In addition to the energy \( E \) and spectral index \( \alpha \), we also have the intrinsic pulse width \( w_I \) which together characterize a FRB. In this section we briefly present a methodology to constrain these parameters for the FRB population using a combination of different FRB observations. The formalism closely follows Bera et al. (2016) to which the reader is referred for details.

For a FRB at redshift \( z \) the observed pulse width \( w = \sqrt{w_{\text{obs}}^2 + w_{\text{DM}}^2 + w_{\text{sc}}^2} \) has three contributions, viz. (i) \( w_I \) stretched by the cosmological expansion \( w_{\text{cos}} = w_I (1+z) \), (ii) for observations at frequency \( \nu_0 \) with channel width \( \Delta \nu_c \), a the dispersion broadening \( w_{\text{DM}} = (8.3 \times 10^6 \text{ DM} \Delta \nu_c)/\nu_0^2 \), and (iii) the scatter broadening \( w_{\text{sc}} \). The exact scattering mechanism in the intervening medium is not well understood, and we consider two scattering models namely (a.) Sc-I which is based on Bhat et al. (2004) that provides an empirical fit to a large number of Galactic pulsar data, we have extrapolated this for the IGM; and (b.) Sc-II which is based on a purely theoretical model proposed by Macquart et al. (2013) considering the turbulent IGM. In both these models \( w_{\text{sc}} \) dominates \( w \) at \( z \geq 0.5 \) (Figure 1 of Bera et al. (2016)), and we expect the observed pulse widths to be correlated with \( z \). However such a correlation is not observed in the Parkes data (Cordes et al. 2016), which motivates us to also consider a third model No-Sc where there is no scattering and \( w_{\text{sc}} = 0 \).

Considering observations with a given telescope, we can use the observed fluence \( F \) to determine the energy of the FRB through the function

\[
E_F(F) = \frac{4\pi r^2}{\phi(\nu) B(\theta)} \sqrt{\frac{w}{1 \text{ ms}}} F
\]

where \( B(\theta) \) is the telescope’s beam pattern evaluated at the FRB’s angular position \( \theta \) and \( \phi(\nu) \) is the frequency profile \( \phi(\nu) \) averaged over the telescope’s observing bandwidth redshifted to the FRB’s rest frame. The comoving distance \( r \) is estimated by considering the \( \Lambda CDM \) cosmology (Planck collaboration et al. 2014). It may be noted that although we have used \( E_F(F) \) in equation (1), the energy \( E \) is also a function of \( z, w_I \) and \( \theta \). Further, the relation between \( E \) and \( F \) also depends on \( \alpha \) through \( \phi(\nu) \).

The telescope can only detect an FRB only if its fluence exceeds a limiting fluence \( (F \geq F_1) \) which is given by

\[
F_1 = [\Delta S]_{\text{rms}} \times (S/N)_{\text{th}} \times 1 \text{ ms}
\]

where \( [\Delta S]_{\text{rms}} \) is the rms noise of the telescope for 1 ms of observation and \((S/N)_{\text{th}}\) is the threshold signal to noise ratio for a detection. The limiting fluence determines the minimum energy \( E_{\text{min}} = E_F(F_1) \) required for an FRB to be detected. As mentioned earlier, this is a function of \( z, w_I \) and \( \theta \) however we shall not show this dependence explicitly.

Considering the FRB population, we model this using \( dN/dE \sim n(E, w_I, z) dE dw_I \) where \( dN \) is the comoving density of the FRB rate for events with energy in the range \( E \) to \( E + dE \) and intrinsic pulse width in the range \( w_I \) to \( w_I + dw_I \). For an observation time \( T \) with the given radio telescope, the number of FRBs \( N(F_1, F_2, z_1, z_2) \) expected to be detected in the fluence interval \( F_1 \) to \( F_2 \) and redshift interval \( z_1 \) to \( z_2 \) is

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2 Inferred from the observed DMs assuming a host galaxy contribution \( DM_{\text{host}} = 50/(1+z) \).
given by
\begin{equation}
N(F_1, F_2, z_1, z_2) = \int_{z_1}^{z_2} d(z_1, z_2) \int d\Omega \int d\omega \int d\Omega \int d\omega \int d\omega \int d\omega 
\end{equation}
which is a generalization of eq. (21) of Bera et al. (2016).

**Redshift distribution:** For a given radio telescope we quantify the observed FRB redshift distribution using the cumulative distribution \( C_{\text{obs}}^M(< z) \) which gives us the fraction of observed FRBs at redshift less than \( z \). This can be predicted by our model using eq. (3) to calculate
\begin{equation}
C_{\text{z}}^M(< z) = \frac{N(F_1, F_{\text{max}}, 0, z)}{N(F_1, F_{\text{max}}, 0, z_{\text{max}})}
\end{equation}
where, \( N(F_1, F_{\text{max}}, 0, z) \) is the number of FRB detections predicted over the redshift range 0 to \( z \) and fluence range \( F_1 \) to \( F_{\text{max}} \). and \( N(F_1, F_{\text{max}}, 0, z_{\text{max}}) \) is the total number of FRB detections predicted by the model. Ideally we would like \( F_{\text{max}} \to \infty \) and \( z_{\text{max}} \to \infty \), however in practice we choose \( F_{\text{max}} \) and \( z_{\text{max}} \) sufficiently large so that we do not expect to observe any FRB with \( F > F_{\text{max}} \) and \( z > z_{\text{max}} \).

**Fluence distribution:** For a given radio telescope, we quantify the observed FRB fluence distribution using the cumulative distribution \( C_{\text{F}}^P(< F) \) which gives us the fraction of observed FRBs having fluence less than \( F \). This can be predicted by our model using eq. (3) to calculate
\begin{equation}
C_{\text{F}}^M(< F) = \frac{N(F_1, F_{\text{max}}, 0, z_{\text{max}})}{N(F_1, F_{\text{max}}, 0, z_{\text{max}})}
\end{equation}
where, \( N(F_1, F_{\text{max}}, 0, z_{\text{max}}) \) is the number of FRB detections predicted over the fluence range 0 to \( F \) and redshift range 0 to \( z_{\text{max}} \), and \( N(F_1, F_{\text{max}}, 0, z_{\text{max}}) \) is defined earlier.

**Kolmogorov-Smirnov Test:** In this work we make the null hypothesis that the observed FRB data is drawn from the distribution predicted by our model which is namely a choice of the function \( n(E, w_i, z) \), the spectral index \( \alpha \) and the scattering model. In our analysis we have considered three different FRB data sets from three different radio telescopes: (1.) the \( N_{\text{data}} = 28 \) FRBs detected by the Parkes, (2.) the \( N_{\text{data}} = 23 \) FRBs detected by ASKAP, and (3.) \( N_{\text{data}} = 12 \) FRBs detected by CHIME. Note that we do not consider the repeating FRB detected at CHIME. We have used the Kolmogorov-Smirnov (KS) test (eg. Conover, W. J. 1999) to accept or reject the null hypothesis based on the goodness of fit between the observed and the predicted cumulative distributions. This is quantified using
\begin{equation}
d_{\chi} = \max|C_{\chi}^M - C_{\chi}^\text{obs}|
\end{equation}
which is the maximum difference between the model cumulative distribution \( C_{\chi}^M \) and the observed cumulative distribution \( C_{\chi}^\text{obs} \). The null hypothesis is rejected at 95% significance when \( d_{\chi} \) exceeds 0.24993 for Parkes, 0.27490 for ASKAP and 0.37543 for CHIME. We have used both the observed redshift distribution \( C_{\text{z}}^\text{obs} \) and the observed fluence distribution \( C_{\text{F}}^\text{obs} \) (eqs. 4 & 5) to test our null hypothesis.

3 **RESULT AND CONCLUSION**

The properties of the FRB population are largely unknown at present. In the present analysis we have made the simplifying assumptions that \( n(E, w_i, z) \) does not evolve with \( z \) over the redshift range of our interest, and the FRBs all have the same energy \( E \) and intrinsic pulse width \( w_i = 1 \) ms. Our models are then characterized by the two parameters \( \alpha \) and \( E \) for which we have used the KS test with the observational data to constrain the allowed region of the parameter space. In order to assess how sensitive our results are to the assumption that \( w_i = 1 \) ms, we have also carried out the analysis for \( w_i = 0.5 \) ms. A large value like \( w_i = 2 \) ms exceeds the pulse width observed for some of the FRBs.

We do not have redshift measurements for most FRBs, and \( z \) is inferred from the observed dispersion measures \( DM \). The FRB redshifts inferred from the observed \( DM \) depend on the choice of the host contribution \( DM_{\text{host}} \) which cannot be separately measured. For our analysis we have assumed a constant value \( DM_{\text{host}} = 50/(1+z) \) for all the FRBs. In order to assess how this assumption affects our constraints on \( \alpha \) and \( E \), we have also performed the analysis for \( DM_{\text{host}} = 0 \). A large value like \( DM_{\text{host}} = 10/(1+z) \) would exceed the measured \( DM \) for some of the FRBs.

Figures 1 and 2 respectively show the redshift (\( C_{\text{z}}^M(z) \)) and fluence (\( C_{\text{F}}^M(F) \)) cumulative distributions for Parkes (left), ASKAP (center) and CHIME (right). The shaded band encompassing the data points shows the allowed region for the model predictions. A model is ruled out at the 95% significance level by the KS test if its predictions lie outside this band even at a single point. We have illustrated this by showing the model predictions for two randomly chosen sets of parameter values (i) \( \alpha = -6 \) and \( E = 2.36 \times 10^{33} \) J and (ii) \( \alpha = -8 \) and \( E = 10^{35} \) J. Considering (i) we see that the predicted redshift cumulative distribution \( C_{\text{z}}^M(z) \) saturates...
at $z \leq 1$ for all telescopes and scattering models $\forall z$ there are no FRBs predicted at $z > 1$. This abrupt cut-off in the redshift distributions is expected, and it corresponds to the redshift at which $E_{\text{min}} = E$. This cut-off redshift however depends on the telescope, scattering model and parameters $E$ and $\alpha$. From the redshift distribution we see that Sc-I is ruled out for Parkes and Sc-II for ASKAP. From the fluence distribution we see that Sc-I is ruled out for both Parkes and CHIME. The No-Sc model is found to be consistent with the redshift and fluence distributions for all the three telescopes. Considering (ii) we see that the redshift distribution extends out to a larger redshift than what is actually observed, the fluence distribution also shows a similar behaviour. This is ruled out for all the telescopes for all the scattering models including No-Sc.

Figure 3 shows the $(\alpha, E)$ plane where the solid red and solid blue contours denote the constraints from the redshift and fluence distributions respectively. The region enclosed within any contour is consistent with the corresponding observations, and the exterior region is ruled out at 95% significance. Considering the Parkes results with the No-Sc model, we see that $\alpha > 2$ is ruled out by both the redshift and the fluence distributions. A narrow energy range with $E \geq 10^{33}$ J is allowed by the redshift distribution, the width of this allowed region increases with decreasing $\alpha$. The fluence distribution imposes independent constraints on the allowed region, here the allowed energies roughly increase with increasing $\alpha$. We see that there is a region of parameter space bounded within $-10 \leq \alpha \leq -2$ and $10^{33}$ J $\leq E \leq 10^{34}$ J for which the predictions are consistent with both the observed redshift and fluence distributions. Considering the other telescopes and scattering models, we see that in all the cases we have a region of parameter space which is consistent with both the redshift and fluence distributions. However, the allowed parameter range is different across the various telescopes and scattering models. The results till now have been restricted to the assumption that $DM_{\text{host}} = 50/(1 + z)$. In order to assess how this assumption affects our results, we also consider $DM_{\text{host}} = 0$ for which the results are shown with dashed lines. We see that the allowed region of parameter space is not very significantly affected if we change the value of $DM_{\text{host}}$.

Considering the No-Sc model (right panels of Figure 3), for each telescope we have identified the region of the $(\alpha, E)$ parameter space which is consistent with both the observed redshift and fluence distribution. The three solid contours in the right panel of Figure 4 show these regions for Parkes, ASKAP and CHIME respectively. The intersection region of these three contours (shaded) demarcates the region of parameter space where the $(\alpha, E)$ values are simultaneously consistent with the FRB redshift and fluence distributions observed at the three telescopes for the No-Sc model. Similarly, we also find an allowed region of parameter space for Sc-II. However the contours for the three telescopes do not overlap for Sc-I and in this case we do not find any parameter value which is allowed. The analysis till now has assumed a constant intrinsic pulse width $w_1 = 1$ ms for all the FRBs. In order to assess how this assumption affects our results, we have also considered $w_1 = 0.5$ ms for which the dashed lines in Figure 4 show the results. We see that the results are not very significantly affected by the change in $w_1$.

In conclusion, Sc-I is ruled out whereas for both Sc-II and No-Sc we have a region of the $(\alpha, E)$ parameter space where the predictions are simultaneously consistent with the FRB redshift and fluence distributions observed at Parkes, ASKAP and CHIME. The allowed $\alpha$ range is bounded by $-7.6 \leq \alpha \leq -4.4$ for Sc-II and $-6.0 \leq \alpha \leq -3.6$ for No-Sc, whereas the allowed $E$ range is bounded by $1.79 \times 10^{33}$ J $\leq E \leq 1.64 \times 10^{34}$ J for Sc-II and $1.79 \times 10^{33}$ J $\leq E \leq 5.41 \times 10^{33}$ J for No-Sc. It may be noted that the average spectral index of $\alpha = -1.6_{-0.2}^{+0.3}$ mentioned in Macquart et al. (2018) is outside the $\alpha$ range allowed by our analysis.

In this Letter we have demonstrated how FRB observations from three different telescopes can be used together to constrain the properties of the FRB population. The entire analysis here is based on a very simple model where all the FRBs have the same energy $E$ and spectral index $\alpha$. While this is possibly an over-simplified model, the allowed energy and spectral index range provides useful inputs for theories of the FRB physical mechanism. We plan to consider more general FRB population models in future work.

Figure 4. The solid contours enclose regions of the $(\alpha, E)$ space where the model predictions are consistent with the FRB redshift and fluence distribution for Parkes (blue), ASKAP (red) and CHIME (green). These assume $w_1 = 1$ ms whereas the dashed lines consider $w_1 = 0.5$ ms. The three panels correspond to different scattering models as indicated.
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