EXTRACTING HOST GALAXY DISPERSION MEASURE AND CONSTRAINING COSMOLOGICAL PARAMETERS USING FAST RADIO BURST DATA

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ABSTRACT

The excessive dispersion measures (DMs) and high Galactic latitudes of fast radio bursts (FRBs) hint toward a cosmological origin of these mysterious transients. Methods of using measured DM and redshift z to study cosmology have been proposed, but one needs to assume a certain amount of DM contribution from the host galaxy (DM_{HG}) in order to apply those methods. We introduce a slope parameter \( \beta(z) \equiv d \ln (\text{DM}_E)/d \ln z \) (where DM_E is the observed DM subtracting the Galactic contribution), which can be directly measured when a sample of FRBs have z measured. We show that \( \langle \text{DM}_{HG} \rangle \) can be roughly inferred from \( \beta \) and the mean values, \( \langle \text{DM}_E \rangle \) and \( \bar{z} \), of the sample. Through Monte Carlo simulations, we show that the mean value of local host galaxy DM, \( \langle \text{DM}_{HG,loc} \rangle \), along with other cosmological parameters (mass density \( \Omega_m \) in the \( \Lambda \)CDM model, and the IGM portion of the baryon energy density \( \Omega_b f_{\text{IGM}} \)), can be independently measured through Markov Chain Monte Carlo fitting to the data.

Key words: cosmological parameters – intergalactic medium

1. INTRODUCTION

Fast radio bursts (FRBs) are a new mysterious class of radio transients observed at frequencies around 1 GHz. They are characterized by short intrinsic durations (∼1 ms), large dispersion measures (DM \( \gtrsim 500 \text{ pc cm}^{-3} \)), and high Galactic latitudes (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014, 2016; Masui et al. 2015; Petroff et al. 2015; Ravi et al. 2015; Champion et al. 2016; Keane et al. 2016). The observed DMs have a large excess with respect to the Galactic value in the high Galactic latitude directions from which the FRBs are observed, suggesting an extragalactic or even a cosmological origin (Thornton et al. 2013; Kulkarni et al. 2014). The observed DM should have a large contribution from the intergalactic medium (IGM). If redshifts of FRBs can be measured, one may combine the DM and z information to perform cosmological studies (Deng & Zhang 2014; Gao et al. 2014; Zheng et al. 2014; Zhou et al. 2014).4

In previous works (Deng & Zhang 2014; Gao et al. 2014; Zhou et al. 2014), in order to constrain the cosmological parameters with FRB observations, one needs to first subtract the host galaxy contribution, DM_{HG} (which includes contributions from the host galaxy interstellar medium and the plasma associated with the FRB source), from the observed value, DM_{obs}, in order to obtain the DM from the IGM, DM_{IGM}. If one has DM_{IGM} and redshift z measured for a sample of FRBs, many interesting cosmological applications are possible. However, DM_{HG} is a poorly known parameter, which depends on the type of the host galaxy, the site of FRB in the host galaxy, the inclination angle of the galaxy disk, and the near-source plasma contribution (Gao et al. 2014; Xu & Han 2015). Another complication is DM_{IGM} depends on \( \Omega_b f_{\text{IGM}} \) (Deng & Zhang 2014; Gao et al. 2014; Zhou et al. 2014), where \( \Omega_b \) is the current baryon mass density fraction of the universe and \( f_{\text{IGM}} \) is the fraction of baryon mass in the IGM. Both values have to be inferred from other cosmological observations.

In this Letter, we study the first derivative of the \( \text{DM} - z \) relation and find that the log \( \text{DM}_E - \log z \) slope (where DM_E is the extragalactic DM of the FRB), \( \beta \equiv d \ln (\text{DM}_E)/d \ln z \), can be used to infer \( \langle \text{DM}_{HG} \rangle \). We further show that \( \langle \text{DM}_{HG,loc} \rangle \) and cosmological parameters (\( \Omega_m \) in \( \Lambda \)CDM cosmology and \( \Omega_b f_{\text{IGM}} \)) can be independently inferred by applying a Markov Chain Monte Carlo (MCMC) fit to a sample of FRBs whose DM and z are measured.

2. METHOD

The observed DM of an FRB is given by (Deng & Zhang 2014; Gao et al. 2014)

\[
\text{DM}_{\text{obs}} = \text{DM}_{\text{MW}} + \text{DM}_{\text{IGM}} + \text{DM}_{\text{HG}},
\]

where DM_{MW}, DM_{IGM}, and DM_{HG} denote the contributions from the Milk Way, IGM, and the FRB host galaxy (including interstellar medium of the host and the near-source plasma, respectively). DM_{MW} can be well constrained with the Galactic pulsar data (Taylor & Cordes 1993), and is a strong function of the Galactic latitude \( |b| \), e.g., DM_{MW} \( \sim 1000 \text{ pc cm}^{-3} \) for \( |b| \sim 0^\circ \), and DM_{MW} \( < 100 \text{ pc cm}^{-3} \) for \( |b| > 10^\circ \). For a well-localized FRB, DM_{MW} can be extracted with reasonable certainty. We then define extragalactic DM of an FRB as

\[
\text{DM}_E \equiv \text{DM}_{\text{obs}} - \text{DM}_{\text{MW}},
\]

Since \( \Lambda \)CDM is consistent with essentially all observational constraints, in the rest of this Letter we focus on this model with \( \Omega_m + \Omega_\Lambda = 1 \) enforced.5 Considering local

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4 So far, only one FRB has its host galaxy’s redshift \( z = 0.492 \) claimed (Keane et al. 2016). The case is, however, controversial (Li & Zhang 2016; Vedantham et al. 2016; Williams & Berger 2016).

5 For more complicated dark energy models, the method proposed in this Letter may be also employed, but additional simulations are needed to see how well different dark energy models may be constrained.
inhomogeneity of IGM, we define the mean DM of the IGM, which is given by (Deng & Zhang 2014)

\[
\langle DM_{\text{IGM}} \rangle = K_{\text{IGM}} \int_0^\infty \frac{f_e(z')(1+z')}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz',
\]

where

\[
K_{\text{IGM}} = \frac{3cH_0\Omega_b f_{\text{IGM}}}{8\pi G m_p},
\]

\(H_0\) is the current Hubble constant, \(\Omega_b\) is the current baryon mass density fraction of the universe, \(f_{\text{IGM}}\) is the fraction of baryon mass in the IGM, \(f_e(z) = (3/4)y_1\chi_{eH}(z) + (1/8)y_2\chi_{eHe}(z)\), \(y_1 \sim 1\) and \(y_2 \approx 4 - 3y_1 \sim 1\) are the hydrogen and helium mass fractions normalized to 3/4 and 1/4, respectively, and \(\chi_{eH}(z)\) and \(\chi_{eHe}(z)\) are the ionization fractions for hydrogen and helium, respectively. For FRBs at \(z < 3\), both hydrogen and helium are fully ionized (Meiksin 2009; Becker et al. 2011). One then has \(\chi_{eH}(z) = \chi_{eHe}(z) = 1\) and \(f_e(z) \approx 7/8\).

In an effort to investigate the first derivative of the DM-z relation, we first define

\[
\alpha(z) \equiv \frac{d \ln \langle DM_{\text{IGM}} \rangle}{d \ln z} = \frac{zf_e(z)(1+z')/\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}{\int_0^\infty f_e(z')(1+z')/\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda} dz'}.
\]

Since \(f_e(z) \approx 7/8\) for \(z < 3\), \(\alpha\) essentially depends only on the cosmological parameters \((\Omega_m, \Omega_\Lambda)\). The \(\langle DM_{\text{IGM}} \rangle-z\) relation and \(\alpha\) as a function of \(z\) are presented in Figure 1 for \(\Omega_m = 0.1, 0.3, 0.5\), respectively. One can see that \(\alpha\) is around 1 at \(z \lesssim 1\). It initially rises and monotonically decreases with \(z\) after reaching a peak.

Observationally, one cannot directly measure \(DM_{\text{IGM}}\) so that \(\alpha\) cannot be directly measured. Since \(DM_E\) and \(z\) are the directly measured parameters, we next define

\[
\beta(z) \equiv \frac{d \ln \langle DM_E \rangle}{d \ln z} = \frac{z}{\langle DM_E \rangle} \left( \frac{d \langle DM_{\text{IGM}} \rangle}{dz} + \frac{d \langle DM_{\text{HI}} \rangle}{dz} \right).
\]

In view of the dispersion of both \(DM_E\) and \(DM_{\text{HI}}\) in different directions at a same \(z\), we have introduced the average values \(\langle DM_{\text{HI}} \rangle\) and \(\langle DM_{\text{HI}} \rangle\) at redshift \(z\) (in practice they are the average values in a certain redshift bin centered around \(z\)). For a host galaxy at redshift \(z\), due to cosmological redshift and time dilation, its observed \(DM_{\text{HI}}\) is a factor of \(1/(1+z)\) of the local one \(DM_{\text{HI,loc}}\) (Ioka 2003; Deng & Zhang 2014). If we assume that the properties of FRB host galaxies have no significant evolution with redshift, then \(d \langle DM_{\text{HI}} \rangle/dz \approx -\langle DM_{\text{HI,loc}} \rangle/(1+z)^2\), and

\[
\beta(z) = \frac{\langle DM_E \rangle - \langle DM_{\text{HI,loc}} \rangle/(1+z)}{\langle DM_E \rangle} \alpha(z) = \frac{\langle DM_{\text{HI,loc}} \rangle}{\langle DM_E \rangle} \frac{z}{(1+z)^2}. \quad (7)
\]

One can see that due to the non-zero value of \(\langle DM_{\text{HI,loc}} \rangle\) and \(a\)-dependent \(\langle DM_E \rangle\), \(\beta(z)\) shows a different behavior from \(\alpha(z)\) (Figure 2): \(\beta(z) \approx 0\) for \(z \ll 1\), and \(\beta(z) \sim \alpha(z)\) for \(z \gg 1\).

Since for standard cosmological parameters, \(\alpha \approx 1\) at \(z \lesssim 1\), one can estimate \(\langle DM_{\text{HI,loc}} \rangle\) using a sample of FRBs at low redshifts. Let us consider a sample of FRBs with \(z < z_c \approx 0.5\). According to Equation (7), one can derive

\[
\langle DM_{\text{HI,loc}} \rangle \approx \frac{(1 - \bar{\beta})(1 + \bar{z})}{1 + 2\bar{z}} \langle DM_E \rangle. \quad (8)
\]

where the over-line symbols denote an average over all the FRBs in the sample at \(z < z_c\), and \(\bar{\beta}\) is the slope of linear fitting in the \(z\) range in log-log space. In particular, for \(z \ll 1\), one has

\[
\langle DM_{\text{HI,loc}} \rangle \approx (1 - \bar{\beta}) \langle DM_E \rangle. \quad (9)
\]

One can see that a sample of FRBs at low \(z\) would give a rough estimate of the host galaxy DM, \(\langle DM_{\text{HI,loc}} \rangle\).

On the other hand, due to \(\langle DM_E \rangle \gg \langle DM_{\text{HI,loc}} \rangle\) at \(z \gg 1\), one has \(\alpha(z) \approx \beta(z)\), which means that one can obtain the
To prove this, in this section we apply Monte Carlo simulations to show that one can use the MCMC method to infer the three unknown parameters. For a given $z$, simulated FRBs might be too dim to detect. Because $\DM$ values would make the pulses more dispersed to evade detection. Therefore, we simulate a number of FRBs, and apply the model to blindly search for input parameters. The likelihood for the fitting parameters is determined by $\chi^2$ statistics, i.e.,

$$\chi^2(\Omega_m, \langle \DM \rangle, \KGM) = \sum \frac{(\DM_i - \langle \DM \rangle)^2}{\sigma_{\DM,i}^2} + \frac{[\sigma_{\DM,i}/(1+z_i)]^2}{\sigma_{\DM,i}^2},$$

where $i$ represents the sequence of FRB in the sample. We minimize $\chi^2$, and then convert $\chi^2$ into a probability density function. We use the software *emcee*\(^6\) to obtain the probability distribution of the fitting parameters. To test the goodness of the method, we assumed that $z_f = 3$ and $\DM = N(100 \text{ pc cm}^{-3}, 20 \text{ pc cm}^{-3})$, and simulated two samples of FRBs. The first sample has $N_{\text{FRB}} = 50$ and the latter has $N_{\text{FRB}} = 500$. The analysis results are presented in the top panel of Figure 3 for $N_{\text{FRB}} = 50$, which give $\Omega_m = 0.38^{+0.04}_{-0.03}$, $\langle \DM \rangle = 77.06^{+15.79}_{-11.51}$ pc cm$^{-3}$, and $\KGM = 992.75^{+30.24}_{-30.90}$ pc cm$^{-3}$. These values are all close to the initial input parameters, suggesting that the MCMC method is a powerful tool to extract the three unknown parameters. For $N_{\text{FRB}} = 500$, as shown in the bottom panel of Figure 3, we obtain $\Omega_m = 0.31^{+0.01}_{-0.01}$, $\langle \DM \rangle = 95.76^{+3.85}_{-3.87}$ pc cm$^{-3}$, and $\KGM = 937.05^{+6.89}_{-6.65}$ pc cm$^{-3}$. The results are even closer to the input values. In Figure 3, the contours are shown at 0.5, 1, 1.5, and 2$\sigma$, respectively.

In order to analyze the effect of $z_f$, we perform simulations with $z_f = 2$ and $z_f = 1$. We also assume that $\DM = N(100 \text{ pc cm}^{-3}, 20 \text{ pc cm}^{-3})$ and $N_{\text{FRB}} = 500$. For $z_f = 2$, as shown in the top panel of Figure 4, we obtain $\Omega_m = 0.31^{+0.04}_{-0.03}$, $\langle \DM \rangle = 102.93^{+6.64}_{-6.71}$ pc cm$^{-3}$, and $\KGM = 931.04^{+21.35}_{-21.10}$ pc cm$^{-3}$. One can see that the results are still close to the input values, even for lower cutoff values at $z_f = 2$ and $z_f = 1$.

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\(^6\) http://dan.iel.fm/emcee/current
Next, we test how the range of $D_{\text{MHG,loc}}$ affects the results. We fix $z_f = 3$ and $N_{\text{FRB}} = 500$, and perform simulations with $D_{\text{MHG,loc}} = N(100 \text{ pc cm}^{-3}, 50 \text{ pc cm}^{-3})$ and $D_{\text{MHG,loc}} = N(200 \text{ pc cm}^{-3}, 50 \text{ pc cm}^{-3})$. For $D_{\text{MHG,loc}} = N(100 \text{ pc cm}^{-3}, 50 \text{ pc cm}^{-3})$, as shown in the top panel of Figure 5, we obtain $\Omega_m = 0.30^{+0.01}_{-0.01}$, $\langle D_{\text{MHG,loc}} \rangle = 108.66^{+7.44}_{-7.34} \text{ pc cm}^{-3}$, and $K_{\text{IGM}} = 921.16^{+7.93}_{-4.29} \text{ pc cm}^{-3}$. For $D_{\text{MHG,loc}} = N(200 \text{ pc cm}^{-3}, 50 \text{ pc cm}^{-3})$, as shown in the bottom panel of Figure 5, we obtain $\Omega_m = 0.31^{+0.01}_{-0.01}$, $\langle D_{\text{MHG,loc}} \rangle = 207.49^{+8.78}_{-4.00} \text{ pc cm}^{-3}$ and $K_{\text{IGM}} = 928.89^{+12.39}_{-11.34} \text{ pc cm}^{-3}$. Our results show that for a certain average value, a larger random fluctuation $\sigma_{\text{MHG,loc}}$ leads to a larger systematic error of $\langle D_{\text{MHG,loc}} \rangle$, but the inferred parameters are still close to the input values. On the other hand, for a certain $\sigma_{\text{MHG,loc}}$, the average value has little effect on the systematic error of $\langle D_{\text{MHG,loc}} \rangle$ but does affect that of $K_{\text{IGM}}$.

4. CONCLUSION AND DISCUSSION

In this Letter, we discuss how to apply DM and $z$ information of future FRBs to study cosmology. Different from previous methods (Deng & Zhang 2014; Gao et al. 2014; Zhou et al. 2014), we do not need to assume the very uncertain host galaxy contribution to DM in the FRB sample. Instead, we show that by considering the slope parameter $\beta$, one may estimate the mean value of host DM, $\langle D_{\text{MHG,loc}} \rangle$, using a sample of low-$z$ FRBs. Combining with FRBs detected at relatively high-$z$ ($z > 1$), one may also constrain $\Omega_m$ (within the framework of the flat $\Lambda$CDM model) and $K_{\text{IGM}}$ (and hence $\Omega_b/\Omega_{\text{IGM}}$). This is because the three parameters mainly define three different properties of the DM-$z$ relation: $\Omega_m$ defines the high-$z$ slope, $K_{\text{IGM}}$ defines the global normalization (y-interception) of the plot in the high-$z$ regime, and $D_{\text{MHG,loc}}$ (along with $K_{\text{IGM}}$) defines the low-$z$ slope and normalization.
We perform Monte Carlo simulations to verify our claim, and find that \(D_{\text{MHG,loc}}\) and cosmological parameters can be indeed extracted from a sample of FRB using MCMC fitting.

Deriving \(D_{\text{MHG,loc}}\) from the data plays an essential role to identify the progenitor systems of FRBs. In our definition, \(D_{\text{MHG,loc}}\) includes the interstellar medium of the FRB host galaxy and near-source plasma. If FRB hosts are Milky-Way-like, since most FRBs come out from high latitudes from their host galaxies, the contribution from the host ISM would be much less than \(100 \text{ pc cm}^{-3}\). If one measures \(\langle D_{\text{MHG,loc}} \rangle \gg 100 \text{ pc cm}^{-3}\) in the future, the main contribution of \(D_{\text{MHG,loc}}\) would be from the near-source plasma. The value of \(\langle D_{\text{MHG,loc}} \rangle\) would therefore place constraints on the various FRB models proposed in the literature (Lorimer et al. 2007; Popov & Postnov 2010; Keane et al. 2012; Kashiyama et al. 2013; Thornton et al. 2013; Totani 2013; Falcke & Rezzolla 2014; Kulkarni et al. 2014; Zhang 2014, 2016; Geng & Huang 2015; Cordes & Wasserman 2016; Dai et al. 2016; Gu et al. 2016; Liu et al. 2016; Lyutikov et al. 2016; Katz 2016; Murase et al. 2016; Piro 2016; Popov & Pshirkov 2016; Wang et al. 2016).

Obtaining a reasonably large sample of FRBs with \(z\) measurements may not be easy, due to the lack of a bright counterpart in other electromagnetic wavelengths hours after the burst (Petroff et al. 2015). There are three possibilities to identify FRB redshifts in the future: (1) with very-long-baseline interferometry observations, one may pin down the precise location (and therefore a possible host galaxy) of an FRB, especially for dedicated observations on the repeating FRBs such as FRB 121102 (Spitler et al. 2016); (2) shorten the delay time of follow-up observations and try to perform multi-wavelength follow-up observations within minutes after the FRB trigger to catch the afterglow in the brightest phase (Yi et al. 2014); (3) appeal to the operation of wide-field FRB
 searches and wide-field X-ray, optical surveys to increase the chance of coincidence of detecting FRB counterparts during the prompt phase to catch the bright early afterglow (Yi et al. 2014) or prompt FRB emission in other wavelengths (Lyutikov & Lorimer 2016). In any case, in the next few years, a few reasonable host galaxy candidates within the positional uncertainty of some FRBs may become available so that the analysis proposed in this Letter may be carried out.

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Figure 5. Same as Figure 3, but for DM_{HG,loc} = N (100 pc cm\(^{-3}\), 50 pc cm\(^{-3}\)) (top panels) and DM_{HG,loc} = N (200 pc cm\(^{-3}\), 50 pc cm\(^{-3}\)) (bottom panels). N_{FRB} = 500 and \(\gamma_f = 3\) are adopted.

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