Cosmology-insensitive estimate of IGM baryon mass fraction from five localized fast radio bursts

Z. Li\textsuperscript{1}, H. Gao\textsuperscript{1}*, J.-J. Wei\textsuperscript{2}, Y.-P. Yang\textsuperscript{3}, B. Zhang\textsuperscript{4}, and Z.-H. Zhu\textsuperscript{1}†

\textsuperscript{1}Department of Astronomy, Beijing Normal University, Beijing 100875, China
\textsuperscript{2}Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210034, China
\textsuperscript{3}South-Western Institute for Astronomy Research, Yunnan University, Kunming 650500, China
\textsuperscript{4}Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA

\textsuperscript{*}E-mail: gaohe@bnu.edu.cn
\textsuperscript{†}E-mail: zhuzh@bnu.edu.cn

ABSTRACT
Five fast radio bursts (FRBs), including three apparently non-repeating ones FRB 180924, FRB 181112, and FRB 190523, and two repeaters, FRB 121102 and FRB 180916.J0158+65, have already been localized so far. We apply a method developed recently by us (Li et al. 2019) to these five localized FRBs to give a cosmology-insensitive estimate of the fraction of baryon mass in the IGM, $f_{\text{IGM}}$. Using the measured dispersion measure (DM) and luminosity distance $d_L$ data (inferred from the FRB redshifts and $d_L$ of type Ia supernovae at the same redshifts) of the five FRBs, we constrain the local $f_{\text{IGM}} = 0.84^{+0.16}_{-0.22}$ with no evidence of redshift dependence. This cosmology-insensitive estimate of $f_{\text{IGM}}$ from FRB observations is in excellent agreement with previous constraints using other probes. Moreover, using the three apparently non-repeating FRBs only we get a a little looser but consistent result $f_{\text{IGM}} = 0.74^{+0.24}_{-0.18}$. In these two cases, reasonable estimations for the host galaxy DM contribution ($\text{DM}_{\text{host}}$) can be achieved by modelling it as a function of star formation rate. The constraints on both $f_{\text{IGM}}$ and $\text{DM}_{\text{host}}$ are expected to be significantly improved with the rapid progress in localizing FRBs.

Key words: intergalactic medium - cosmological parameters

1 INTRODUCTION
Fast radio bursts (FRBs) are intense bursts of radio waves with millisecond durations (Lorimer et al. 2007; Thornton et al. 2013; Petroff et al. 2015, 2016). Their large values of the dispersion measure (DM), which are much greater than expected contributions from the Milky Way interstellar medium alone (Dolag et al. 2015), suggest their extragalactic or even cosmological origin. Therefore, the observed DM of an FRB should at least have a significant contribution from the intergalactic medium (IGM). It is implied that, based on the DM_{\text{IGM}} - z relation, the FRBs are typically at distances of the order of gigaparsec (Ioka 2003; Inoue 2004; Deng & Zhang 2014; Zheng et al. 2014; Deng & Zhang 2014; Muñoz & Loeb 2018), the cosmological origin of FRBs allows them to become promising tools for studying the universe and fundamental physics, e.g. baryon density and spatial distribution (Mcquinn 2014; Deng & Zhang 2014; Muñoz & Loeb 2018), dark energy (Gao et al. 2014; Zhou et al. 2014; Walters et al. 2018; Wei et al. 2018), cosmic ionization history (Deng & Zhang 2014; Zheng et al. 2014), the large-scale structure of the universe (Masui & Sigurdson 2015), the Einstein’s equivalence principle (Wei et al. 2015; Nusser 2016; Tingay & Kaplan 2016), the rest mass of the photon (Wu et al. 2016; Shao & Zhang 2017), the cosmic proper distance measurements (Yu & Wang 2017), as well as constraints on the magnetic fields in the IGM (Akahori et al. 2016). Because of another two properties of these mysterious transients, i.e. short durations ($\sim (1 - 10)$ms) (Lorimer et al. 2007; Keane et al. 2011; Thornton et al. 2013; Spitler et al. 2014; Petroff et al. 2015; Ravi et al. 2015; Champion et al. 2016; Petroff et al. 2016; Spitler et al. 2016) and high event rate ($\sim 10^3 - 10^4$ per day all sky) (Thornton et al. 2013; Champion et al. 2016), lensed FRBs have been proposed as a probe of compact dark matter (Munoz et al. 2016; Wang & Wang 2018), motion of the FRB source (Dai & Lu 2017), and precision cosmology (Li et al. 2018; Liu et al. 2019).

More recently, Li et al. (2019) proposed a method to probe the intergalactic medium (IGM) by estimating the fraction of baryon in the IGM, $f_{\text{IGM}}$, using the putative sample of FRBs with both of their DMs and luminosity distances.
available. It should be emphasized that, since $d_L/\text{DM}$ essentially does not depend on cosmological parameters, this method can determine $f_{\text{DM}}$ in a cosmology-insensitive way. By means of Monte Carlo simulations, it was shown that an unbiased and cosmology-insensitive estimate of the present value of $f_{\text{DM}}$ can be obtained from a sample of FRBs with joint measurements of DM and $d_L$. In addition, such a method can also simultaneously lead to a measurement of the mean value of DM contributed from the local host galaxy. In practice, it should be also pointed out that localization and redshift measurement of bursts play an essential role for applying this approach. Back then, localization was only made for the first repeater FRB 121102, which has $z \sim 0.19$ (Spitler et al. 2016; Scholz et al. 2016; Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017; Zhang & Wang 2019; Wang & Zhang 2019).

Recently, another three apparently non-repeating FRBs\(^1\) and one repeating source were localized. First, FRB 180924 was localized with the Australia Square Kilometer Array Pathfinder (ASKAP) to a position 4 kpc from the center of a luminous and massive galaxy at redshift 0.3214 (Bannister et al. 2019). The observed DM of the burst, is 361.42 ± 0.06 pc cm\(^{-3}\) and the pulse width is 1.30 ± 0.09 ms. The position of the burst is in one of the high Galactic latitude fields targeted by ASKAP (Galactic longitude $b = 0.74247^\circ$, Galactic latitude $l = -49.41478^\circ$). The Milky Way DM disk and halo components estimated from the NE2001 model (Cordes & Lazio 2002) for this position are 40.5 pc cm\(^{-3}\) and 30 pc cm\(^{-3}\), respectively. Second, FRB 190523 was localized by the Deep Synoptic Array ten-antenna prototype (DSA-10) to a few-arsecound region containing a single massive galaxy at redshift 0.66 (Ravi et al. 2019). The burst was detected at a DM of 760.8±0.6 pc cm\(^{-3}\) and the pulse width is 0.42 ± 0.05 ms. The position of the burst is Galactic longitude $b = 117.03^\circ$, Galactic latitude $l = 44^\circ$. In this direction, the Milky Way disk and the Milky Way ionised halo contribute 37 pc cm\(^{-3}\) and 50 – 80 pc cm\(^{-3}\), respectively. Therefore, the extragalactic DM of this burst is between 644 and 674 pc cm\(^{-3}\). Third, FRB 181112 was detected by the Commensal Real-time ASKAP Fast Transients (CRAFT) survey (Prochaska et al. 2019). The burst sweep yields an estimate of the FRB dispersion measure $DM = 589.27 ± 0.03$ pc cm\(^{-3}\). The real-time detection precisely localized the burst to a sky position Galactic longitude $b = 342.6^\circ$, Galactic latitude $l = -47.7^\circ$. The Milky Way disk and the Milky Way ionised halo contribute 102 pc cm\(^{-3}\) and ∼ 30 pc cm\(^{-3}\) in this sky position. The image centered on FRB 181112 obtained with the FOcal Reducer/low dispersion Spectrograph 2 (FORS2) instrument on the Very Large Telescope (VLT) shows the presence of a galaxy coincident with this burst, previously catalogged by the Dark Energy Survey (DES) as DES J214923.66-525815.28. More interestingly, the DES and FORS2 data also show that a luminous galaxy (DES J214923.89-525810.43) is ∼ 5′′ to the North of the FRB event. Follow-up spectroscopy with the FORS2 instrument obtained that the redshift of the former galaxy (host galaxy of this burst) is $z = 0.47550$, and the redshift of the latter (i.e. the foreground galaxy) is $z = 0.3674$. This foreground galaxy contributes $50 – 120$ pc cm\(^{-3}\), which does not dominate the DM of this event and depends on assumptions of density profile and the total mass of the halo gas. In our following analysis, we approximately take $85 ± 35$ pc cm\(^{-3}\) to account for the DM contribution and corresponding uncertainty of this foreground galaxy. Finally, a second repeater, FRB180916.30158+6-65, was localized recently to be located in a star-forming region of a nearby massive galaxy at $z = 0.0337$ (Marcote et al. 2020). In the direction of this burst, the Milky Way disk (halo) contributes 199 (∼ 50 – 80) pc cm\(^{-3}\).

In the following, we will apply the method of Li et al. (2019) to perform a cosmological-model-insensitive estimate of the fraction of baryons in the IGM using the five FRBs with redshift measurements.

\section{Methods}

The method has been proposed in Li et al. (2019) and below we briefly summarize it.

For a localized FRB, we can get the observed extragalactic DM with a considerable precision by deducting Milky Way portion, DM\(_{\text{MW}}\), from DM\(_{\text{obs}}\) (Thornton et al. 2013; Deng & Zhang 2014; Yang & Zhang 2016).

\begin{equation}
DM_{\text{ext,obs}} = DM_{\text{obs}} - DM_{\text{MW}}.
\end{equation}

For sources at high Galactic latitude $(|b| > 10^\circ)$, the average uncertainty of the DM contribution from the Milky Way and halo, $\sigma_{\text{MW}}$, is about 30 pc cm\(^{-3}\) (Manchester et al. 2005). DM\(_{\text{ext,obs}}\) and $\sigma_{\text{ext}}$ for all five localized FRBs are shown in the left panel of Fig. 1. Moreover, the observed extragalactic DM actually consists of two contributions, i.e. the IGM portion and the host galaxy portion. Therefore, for a localized FRB, DM\(_{\text{IGM}}\) in the certain direction can be in principle measured by deducting the host galaxy portion from the observed extragalactic DM (Ioka 2003; Deng & Zhang 2014).

\begin{equation}
DM_{\text{IGM,obs}} = DM_{\text{ext,obs}} - \frac{DM_{\text{host,loc}}}{1 + z}.
\end{equation}

The value of DM\(_{\text{host,loc}}\) and its uncertainty are intractable parameters since they are poorly known and dependent on many factors, e.g. the type of the host galaxy, the inclination angle of the galaxy disk, the site of FRB in the host, and the near-source plasma (Luan & Goldreich 2014; Katz 2016; Piro 2016; Yang & Zhang 2016; Metzger et al. 2017; Piro & Burke-Spolaor 2017; Yang & Zhang 2017; Yang et al. 2017). For a given type of host galaxy, the magnitude of DM\(_{\text{host,loc}}\) along a certain line of sight depends on the electron density and size of the galaxy (Manchester et al. 2006; Xu & Han 2015). The former one is proportional to the $H_0$ luminosity of the galaxy, which scales with the star formation rate (SFR) (Kennicutt, Tamblyn & Congdon 1994; Madau, Pozzetti & Dickinson 1998). Therefore, for simplicity and generality, here we model DM\(_{\text{host,loc}}\) as a function with respect to redshift by assuming that the rest-frame DM distribution accommodates the evolution of the SFR history (Luo et al. 2018).

$DM_{\text{host,loc}}(z) = DM_{\text{host,loc}}(0) \frac{\text{SFR}(z)}{\text{SFR}(0)}$. 

\(^1\) Since all FRBs can be in principle repeating, here we use "apparently non-repeating FRBs" to refer to the sources from which only one burst was detected so far. In the following text, this population is also referred as non-repeating or single bursts.
and adopt a continuous form of a broken power law for it \citep{Yuksel2008}. In our following analysis, \(DM_{\text{host,loc}}\) is treated as a free parameter to be fitted. In this case, we write the uncertainty of \(DM_{\text{IGM}}\) as

\[
\sigma_{\text{IGM}}^2 = \sigma_{\text{obs}}^2 + \sigma_{\text{MW}}^2 + \sigma_{\text{int}}^2.
\]

For the sample of these five localized FRBs, as shown in Fig. 1, observed \(DM_{\text{loc}}\) has significant scatter. This systematical scatter might originate from the diversity of host galaxy contribution or the IGM fluctuation. Therefore, we introduce \(\sigma_{\text{int}}\) in Eq. 3 to account for this scatter and the magnitude of it is determined in the following \(\chi^2\)-statistics analysis by ensuring the reduced \(\chi^2\) (\(\chi^2/\text{dof}, \text{dof}: \text{degree of freedom}\)) is approximately to be unity.

In theory, the IGM portion depends on the cosmological distance scale the burst propagates through and the fraction of ionized electrons in hydrogen and helium on the path. If both hydrogen and helium are fully ionized (valid below \(z \sim 3\)), it can be expressed as

\[
DM_{\text{IGM}}(z) = \frac{21cH_0\Omega_b}{64\pi G\rho_m} \int_0^z \frac{f_{\text{IGM}}(z')(1 + z')dz'}{\sqrt{\Omega_m(1 + z')^3 + \Omega_\Lambda}}.
\]

It is known that \(f_{\text{IGM}}\) evolves with redshift as massive haloes are more abundant in the late universe \citep{Mcquinn2014, ProchaskaZheng2019}. Therefore, we characterize the growth of \(f_{\text{IGM}}\) with redshift as a mildly increasing function, \(f_{\text{IGM}}(z) = f_{\text{IGM}}(1 + \alpha z/(1 + z))\) \citep{Li2019}. Here, the parameter \(\alpha\) is responsible for quantifying the evolution of \(f_{\text{IGM}}\). The fact that \(f_{\text{IGM}}\) grows with redshift requires \(\alpha > 0\).

The \(DM_{\text{IGM}}-z\) relation has been widely used for probing baryon density and cosmography \citep{Mcquinn2014, DengZhang2014, Gao2014, Zhou2014, Walters2018, Wei2018}. However, almost all these works have encountered the degeneracy between the fraction of baryon in the IGM, \(f_{\text{IGM}}\), and cosmological parameters. This degeneracy is intractable when the standard cosmological model itself is very uncertain, which is strongly implied by the well-known Hubble constant tension \citep{PlanckCollaboration2018, Riess2019}. Therefore, in order to alleviate the dependence of estimation for \(f_{\text{IGM}}\) from the \(DM_{\text{IGM}}-z\) relation on cosmology, the combination of DM and luminosity distance measurements of FRBs, \(d_l/DM_{\text{IGM}}\), has been proposed to estimate \(f_{\text{IGM}}\) in a cosmological-model-insensitive way \citep{Li2019}\footnote{In \citep{Li2019}, we have concluded that, compared to the \(DM_{\text{IGM}}-z\) relation, \(d_l/DM_{\text{IGM}}\) is insensitive to the dark energy equation of state parameter, \(w\), by a factor of 10. Here, we further check the sensitivities of the \(DM_{\text{IGM}}-z\) relation and \(d_l/DM_{\text{IGM}}\) to cosmology by considering variations in the matter density parameter, \(\Omega_m\), and the same conclusion is obtained. It should be pointed out that, in this work, the term “cosmology-insensitive” only implies that results here are insensitive to cosmological-model parameters, such as \(\Omega_m\) and \(w\).}

By denoting \(d_l/DM_{\text{IGM}} = R\), we obtain estimates for parameters by carrying out the following \(\chi^2\) analysis

\[
\chi^2 = \sum_i \frac{(R_{\text{obs},i} - R_{\text{th},i})^2}{\sigma_{\text{tot},i}^2}.
\]

where \(R_{\text{obs}} = d_l/DM_{\text{IGM,obs}}, R_{\text{th}} = d_l/DM_{\text{IGM,th}}\), and

\[
\chi^2_{\text{tot}} = \frac{\sigma_{\text{obs}}^2}{DM_{\text{IGM,obs}}} + \frac{d_{\text{obs}}^2}{DM_{\text{IGM,obs}}} + \frac{d_{\text{tot}}^2}{DM_{\text{IGM,obs}}}.
\]

Here, for each localized FRB, we obtain its distance by binning the observed distances of the two SNe Ia with redshifts closest to the five FRBs. The Hubble diagram of the Pantheon SN Ia \citep{Sconie2018} and binned distances for the latest localized FRBs are shown in the right panel of Fig. 1. Using the method proposed in \citep{Li2019}, we apply the observational data of the five localized FRBs to perform a cosmology-insensitive estimate of \(f_{\text{IGM}}\).

3 RESULTS

We first obtain the constraints from all five FRBs with redshift measurements. The results are shown in Fig. 2 \citep[light blue contours]{}. In this case, we obtain that the present value of \(f_{\text{IGM}}\) is constrained to be \(f_{\text{IGM,0}} = 0.84^{+0.16}_{-0.22}\). This is well consistent with previous results obtained from observations \citep[e.g.][]{Fukugita1998, Fukugita2004}. Moreover, constraint on \(f_{\text{IGM}}\), the IGM baryon mass fraction from FRB observations, is insensitive to the dark energy equation of state \(w\), by a factor of 10. Here, we further check the sensitivities of the \(DM_{\text{IGM}}-z\) relation and \(d_l/DM_{\text{IGM}}\) to cosmology by considering variations in the matter density parameter, \(\Omega_m\), and the same conclusion is obtained. It should be pointed out that, in this work, the term “cosmology-insensitive” only implies that results here are insensitive to cosmological-model parameters, such as \(\Omega_m\) and \(w\).}

In this \(\chi^2\) fitting analysis, we also obtain an estimation for the average IGM fluctuation in directions of these five FRBs, \(\sigma_{\text{tot}} > 40 \text{ pc cm}^{-3}\). That is, for these five localized FRBs, the systematical scatter due to IGM fluctuation is much smaller than that predicted by simulations in \cite{Mcquinn2014, Dolag2015}. Secondly, since the population of single bursts might be different from the one of repeaters\footnote{Note that whether or not all FRBs have repeating nature is still under debate \citep{Palaniswamy2018, Caleb2019, James2019}. \cite{Ravi2019} showed that the volumetric occurrence rate of FRBs that have not been observed to repeat so far is larger than the rates of candidate cataclysmic progenitor events, suggesting that most observed FRBs may originate from repeating sources.}, we also constrain \(f_{\text{IGM}}\) by considering the three localized single bursts. Results are also shown in Fig. 2 \citep[red contours]{}. It suggests that a smaller \(f_{\text{IGM,0}} = 0.74^{+0.24}_{-0.43}\) and a larger \(\alpha = 0.89^{+1.44}_{-0.86}\) are obtained. These results are also in good consistency with what obtained in \cite{Fukugita1998, Fukugita2004}. Moreover, constraint on \(\alpha\) slightly suggests the redshift dependence of \(f_{\text{IGM}}\). At the same time, an estimation for the value of host galaxy contribution DM is \(DM_{\text{host,loc}} = 34^{+39}_{-33} \text{ pc cm}^{-3}\), which is in good agreement with what inferred from observations of the latest localized single bursts \citep{Bannister2019, Ravi2019}. It should be clarified that estimations for the host galaxy contribution DM are based on the assumption for the redshift dependence of the rest-frame DM distribution on the evolution of the SFR history.
Taking the constraints from all five localized FRBs into consideration, in Fig. 3, we plot extragalactic DM and IGM DM in contrast with \( f_{\text{IGM},0} \), which predictions from different \( f_{\text{IGM},0} \) in the 1\( \sigma \) range. It is found that derived DM \( \text{ext} \) of all five bursts are above the best-fit (black solid) line. After deducting DM \( \text{host,loc} \) from DM \( \text{ext} \), DM \( f_{\text{IGM}} \) of all five bursts are evenly distributed around the best-fit line. These results suggest that the estimated \( f_{\text{IGM}} \) and DM \( f_{\text{host,loc}} \) are reliable. In addition, some DM \( f_{\text{IGM}} \), which have been widely used in the literature, are also plotted for the sake of comparison. It is obtained that the DM \( f_{\text{IGM}} \) relation given by (Deng & Zhang 2014), DM \( \sim 855 \) pc cm\(^{-3} \) (Zhang 2018), with the consideration of He ionization history and \( f_{\text{IGM}} = 0.83 \) is in excellent agreement with cosmology-insensitive estimations from the latest observations. However, the relation with \( f_{\text{IGM}} = 1.0 \) given in (Inoue 2004), DM \( \sim 1000 \) pc cm\(^{-3} \), is marginally outside the 1\( \sigma \) range of the constraint. Furthermore, the relation with \( f_{\text{IGM}} = 1.0 \) and without considering He ionization history given in (Ioka 2003), DM \( \sim 1200 \) pc cm\(^{-3} \), is in significant tension with the latest FRB observations.

4 CONCLUSIONS AND DISCUSSIONS

In this paper, we investigate cosmology-insensitive constraints on the fraction of baryons in the IGM, \( f_{\text{IGM}} \), from joint measurements of luminosity distances and dispersion measures of the latest localized FRBs, including the two repeaters, i.e. FRB 121102 and 180916.0158+65, and three single bursts, i.e. FRB 180924, 181112, and FRB 190523. We estimate \( f_{\text{IGM}} \) using observations of all these five bursts and obtain \( f_{\text{IGM},0} = 0.84^{+0.16}_{-0.22} \). This constraint from FRB observations is well consistent with those obtained from other probes (Fukugita et al. 1998; Fukugita & Peebles 2004; Shull et al. 2012; Hill et al. 2016). For the three localized single FRBs only, we obtain \( f_{\text{IGM},0} = 0.74^{+0.24}_{-0.18} \), which is looser but still consistent with the five-FRB constraint as well as the constraints derived from previous methods. For these cosmology-insensitive estimations, it is also necessary to point out that they are obtained with the best-fit cosmology from the latest Planck CMB observations. In fact, parameters in this underlying cosmology also degenerate with

Figure 1. Left: Extragalactic dispersion measures of all five localized FRBs. Right: The Hubble diagram of Pantheon SNe Ia and luminosity distances binned from the two nearest SNe Ia for five FRBs with their host galaxy identified.

Figure 2. Joint contours for all fitted parameters from the latest localized FRBs.

Figure 3. Extragalactic DM and IGM DM in contrast with DM \( f_{\text{IGM}} \) predictions from different \( f_{\text{IGM},0} \).
those we are interested here and the complete set of parameters should be \( (H_0, \Omega_b, f_{\text{igm}}, a, \Delta M_{\text{host,loc}}) \). However, these parameters would be very loosely constrained from only five localized FRBs. Therefore, at this moment, we focus on the estimate of IGM baryon mass fraction, which is one of the most promising benefits of localized FRBs, by taking \( H_0 \) and \( \Omega_b \) from the latest Planck CMB observations as priors. Alternatively, all concerning parameters would be well constrained from a large number of localized FRBs which are likely to be achieved in the near future.

Redshift measurements or localizations of a large sample of FRBs are essential for using this method to perform cosmology-insensitive estimate of \( f_{\text{igm}} \). A substantial population of repeating FRBs will be detected by wide-field sensitive radio telescopes, such as the CHIME/FRB instruments (The CHIME/FRB Collaboration 2019a,b,c). It suggests that a considerable number of repeaters with redshifts measured will be accumulated in the near very future. It is more exciting that radio interferometers, such as ASKAP and DSA-10, has led to direct localizations of three single bursts. Based on the detection rate, it is likely to collect a large number of localized FRBs in a short time. As suggested in (Hallinan et al. 2019), a world-leading radio survey telescope and multi-messenger discovery engine for the next decade, DSA-2000, will simultaneously detect and localize \( \sim 10^4 \) fast radio bursts each year. It is foreseen that the constraints on concerning parameters, especially on \( f_{\text{igm}} \), will be significantly improved with the rapid progress in localizing FRBs.

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