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Fast Radio Burst Energetics and Detectability from High Redshifts

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Abstract

We estimate the upper limit redshifts of known fast radio bursts (FRBs) using the dispersion measure (DM)-redshift (z) relation and derive the upper limit peak luminosity L_p and energy E of FRBs within the observational band. The average z upper limits range from 0.17 to 3.10, the average L_p upper limits range from $1.24 \times 10^{42}\,\mathrm{erg\,s^{-1}}$ to $7.80 \times 10^{44}\,\mathrm{erg\,s^{-1}}$, and the average E upper limits range from 6.91×10^{39} erg to 1.94×10^{42} erg. FRB 160102 with $\mathrm{DM} = 2596.1 \pm 0.3\,\mathrm{pc\,cm^{-3}}$ likely has a redshift greater than 3. Assuming that its intrinsic DM contribution from the host and FRB source is $\mathrm{DM_{host}} + \mathrm{DM_{scr}} \sim 100\,\mathrm{pc\,cm^{-3}}$, such an FRB can be detected up to $z \sim 3.6$ by Parkes and the Five-hundred-meter Aperture Spherical radio Telescope (FAST) under ideal conditions up to $z \sim 10.4$. Assuming the existence of FRBs that are detectable at $z \sim 15$ by sensitive telescopes such as FAST, the upper limit DM for FRB searches may be set to $\sim 9000\,\mathrm{pc\,cm^{-3}}$. For single-dish telescopes, those with a larger aperture tend to detect more FRBs than those with a smaller aperture if the FRB luminosity function index α_{L} is steeper than 2, and vice versa. In any case, large-aperture telescopes such as FAST are more capable of detecting high-z FRBs, even though most of FRBs detected by them are still from relatively low redshifts.

Key words: radio continuum: general

1. Introduction

Fast radio bursts (FRBs; Lorimer et al. 2007; Thornton et al. 2013; Petroff et al. 2015, 2016; Katz 2018) are mysterious radio transients with excess dispersion measure (DM) with respect to the Galactic values. The localization of the only repeating source, FRB 121102 (Scholz et al. 2016; Spitler et al. 2016; Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017), confirmed the cosmological origin of at least this source (at $z = 0.19$), and there is good reason to believe that most, if not all, FRBs also originate from cosmological distances (Thornton et al. 2013; Caleb et al. 2016; Macquart & Ekers 2018). If many FRBs are localized so that their redshifts are measured, the combined z and DM information of these events can be used to directly measure the baryon number density of the universe (Deng & Zhang 2014; Keane et al. 2016) and its large-scale fluctuation (McQuinn 2014). It can also constrain the cosmological parameters together with other cosmic probes (Gao et al. 2014; Zhou et al. 2014; Walters et al. 2018), constrain the cosmic ionization history (Deng & Zhang 2014; Zheng et al. 2014; Fialkov & Loeb 2016), measure the Hubble Constant and cosmic curvature if some repeating FRBs are gravitationally lensed (Li et al. 2018b), and even constrain Einstein's Weak Equivalence Principle (WEP; Wei et al. 2015) and the rest mass of the photon (Wu et al. 2016; Shao & Zhang 2017). It is not known whether FRBs can be made at high redshifts. Certain progenitor models (e.g., Zhang 2014; Connor et al. 2016; Cordes & Wasserman 2016; Metzger et al. 2017) make connections between FRBs and young neutron stars produced from supernovae or gamma-ray bursts (GRBs), so that their birth rate may track the star formation history of the universe. Because GRBs with redshifts up to 9.4 have been detected (e.g., Cucchiara et al. 2011), it is possible that some FRBs may be generated at high redshifts within these scenarios. Detecting high-redshift (e.g., $z > 7$) FRBs is extremely valuable, as they can be used to probe the reionization history of the universe and place the most stringent constraints on the WEP and the mass of the photon.

Many current and upcoming facilities have FRB detections as one of their leading scientific goals (e.g., Parkes Petroff et al. 2016), the transient Universe in real Time with Molongo Observatory Synthesis Telescope (UTMOST; Bailes et al. 2017), the Canadian Hydrogen Intensity Mapping Experiment (CHIME; Amiri et al. 2018), the Five-hundred-meter Aperture Spherical radio Telescope (FAST; Li et al. 2018b), the Australian Square Kilometre Array Pathfinder (ASKAP; Johnston et al. 2009), MeerKAT (Booth et al. 2009), Square Kilometer Array (SKA; Macquart et al. 2015; Fialkov & Loeb 2017). It is interesting to investigate from what redshifts the FRBs can be detected with these telescopes.

2. Estimates of Z and E of Known FRBs

The observed DM of an FRB can be broken down to

$$\mathrm{DM} = \mathrm{DM_{MW}} + \mathrm{DM_E} \tag{1}$$

where

$$\mathrm{DM_E} = \mathrm{DM_{IGM}} + \frac{\mathrm{DM_{host}} + \mathrm{DM_{src}}}{1+z} \tag{2}$$

is the external DM contribution outside the Milky Way galaxy, and $\mathrm{DM_{host}}$ and $\mathrm{DM_{src}}$ are the DM contributions from the FRB host galaxy and source environment, respectively, in the cosmological rest frame of the FRB. The measured values of both are smaller by a factor of $(1 + z)$ (Ioka 2003; Deng & Zhang 2014). The intergalactic medium (IGM) portion of DM is related to the distance (redshift) of the source through (Deng & Zhang 2014)

$$\mathrm{DM_{IGM}} = \frac{3cH_0\Omega_b f_{\mathrm{IGM}}}{8\pi G m_p}\int_0^z \frac{\chi(z)(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}} \tag{3}$$

in the flat ΛCDM universe (i.e., the dark energy equation of state parameter $w = -1$), where Ω_b is the baryon density, H_0 is

Hubble constant, $f_{\rm IGM} \sim 0.83$ is the fraction of baryons in the IGM (Fukugita et al. 1998),[3]

$$\chi(z) = \frac{3}{4} y_1 \chi_{e,{\rm H}}(z) + \frac{1}{8} y_2 \chi_{e,{\rm He}}(z) \quad (4)$$

denotes the free electron number per baryon in the universe, with $\chi_{e,{\rm H}}$ and $\chi_{e,{\rm He}}$ denoting the ionization fraction of hydrogen and helium, respectively, and $y_1 \sim y_2 \sim 1$ denoting the possible slight deviation from the 3/4-1/4 split of hydrogen and helium abundance in the universe. If both hydrogen and helium are fully ionized (valid below $z \sim 3$), one has $\chi(z) \simeq 7/8$. Adopting the latest Planck results (Planck Collaboration et al. 2016) for the ΛCDM cosmological parameters, i.e., $H_0 = 67.74 \pm 0.46\ {\rm km\ s^{-1}\ kpc^{-1}}$, $\Omega_b = 0.0486 \pm 0.0010$, $\Omega_m = 0.3089 \pm 0.0062$, $\Omega_\Lambda = 0.6911 \pm 0.0062$, Equation (3) has the numerical value

$$\begin{aligned} {\rm DM_{IGM}} &\simeq 1112\ {\rm pc\ cm^{-3}} f_{\rm IGM} \chi F(z) \\ &\simeq 807\ {\rm pc\ cm^{-3}} \frac{f_{\rm IGM}}{0.83} \frac{\chi}{7/8} F(z), \end{aligned} \quad (5)$$

where

$$F(z) = \int_0^z \frac{(1+z)dz}{[\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}}, \quad (6)$$

which lies in the range 1–1.12 for $z < 3$. If one adopts an average value $F(z) \sim 1.06$, one has ${\rm DM_{IGM}} \sim 1168\ {\rm pc\ cm^{-3}}\ f_{\rm IGM}\chi z = 855\ {\rm pc\ cm^{-3}}\ (f_{\rm IGM}/0.83)(\chi/(7/8))z$ for $z < 3$. In the FRB literature, $z \sim {\rm DM_E}/(1200\ {\rm pc\ cm^{-3}})$ has been adopted (Caleb et al. 2016; Petroff et al. 2016) to estimate the upper limit of the FRB redshifts based on the earlier calculations by Ioka (2003) and Inoue (2004). These calculations have assumed that essentially all baryons are in the IGM ($f_{\rm IGM} \sim 1$) and that the universe is composed of hydrogen only ($\chi = 1$), which significantly underestimates the redshift upper limit z for a given ${\rm DM_E}$ (by a factor of $\sim 0.83 \cdot (7/8) \sim 0.73$). According to our results, a rough estimate

$$z \sim {\rm DM_{IGM}}/855\ {\rm pc\ cm^{-3}} \quad (7)$$

is recommended for $z < 3$, which has a ∼6% error. Notice that this relation is valid on average. Due to the existence of large-scale structures, different lines of sight may give different ${\rm DM_{IGM}}$ values for the same z (McQuinn 2014). The variation is redshift-dependent, and can be up to ∼40% at $z \sim 1$ and drops at higher redshifts. If one adopts the ∼40% variation, the conversion factor 855 would be in the range ∼(510–1200).

In order to derive the ${\rm DM_{IGM}}$ of an FRB, one needs to know ${\rm DM_{host}} + {\rm DM_{src}}$. This is difficult to derive from an individual FRB, but may be derived statistically using a sample of FRBs (Yang & Zhang 2016; Yang et al. 2017). The observations of FRB 121102 (Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017) and a statistical study (Yang et al. 2017) suggest that this sum is not small, which is comparable to ${\rm DM_{IGM}}$ for FRB 121102 (if the true ${\rm DM_{IGM}}$ of the source is close to the average value derived in Equation (3)). In any case, ${\rm DM_E}$ can be used to derive an average upper limit of ${\rm DM_{IGM}}$, and hence an average upper limit of z, of a particular FRB (again noting the fluctuations of ${\rm DM_{IGM}}$ along different lines of sight; McQuinn 2014). As DM increases, this average upper limit gets closer to the true value due to the $(1+z)$ suppression factor of ${\rm DM_{host}} + {\rm DM_{scr}}$. The average z upper limits of the published FRBs (extracted from the FRB catalog, Petroff et al. 2016) are presented in Table 1. The external ${\rm DM_E}$ values are directly taken from the FRB catalog, which were presented in the original papers that reported the discovery of each FRB (Petroff et al. 2016, and references therein). In those original papers, some authors have used the Galactic electron density model NE2001 (Cordes & Lazio 2002) while some others used YMW17 (Yao et al. 2017). The ${\rm DM_{MW}}$ values derived from the two models usually agree with each other, but could be very different for some FRBs. In any case, because ${\rm DM_{MW}}$ is usually a small portion of the total DM, the derived ${\rm DM_E}$ from the two Galactic electron density models would not differ significantly, and the conclusions presented in this Letter are essentially not affected. In the derivations of ${\rm DM_E}$ of these original papers, the DM contribution from the Galactic halo (e.g., Dolag et al. 2015) was not deducted.

With the z upper limit, one can derive the upper limit of the isotropic peak luminosity and isotropic energy of an FRB within the observed bandwidth, which read

$$\begin{aligned} L_p &\simeq 4\pi D_{\rm L}^2 S_{\nu,p} \nu_c \\ &= (10^{42}\ {\rm erg\ s^{-1}}) 4\pi \left(\frac{D_{\rm L}}{10^{28}\ {\rm cm}}\right)^2 \frac{S_{\nu,p}}{\rm Jy} \frac{\nu_c}{\rm GHz}, \end{aligned} \quad (8)$$

$$\begin{aligned} E &\simeq \frac{4\pi D_{\rm L}^2}{(1+z)} \mathcal{F}_\nu \nu_c \\ &= (10^{39}\ {\rm erg}) \frac{4\pi}{(1+z)} \left(\frac{D_{\rm L}}{10^{28}\ {\rm cm}}\right)^2 \frac{\mathcal{F}_\nu}{\rm Jy \cdot ms} \frac{\nu_c}{\rm GHz}, \end{aligned} \quad (9)$$

where $S_{\nu,p}$ is the specific peak flux (in units of ${\rm erg\ s^{-1}\ cm^{-2}\ Hz^{-1}}$ or Jy), and $\mathcal{F}_\nu = S_{\nu,p}\tau_{\rm obs}$ is the specific fluence (in units of ${\rm erg\ cm^{-2}\ Hz^{-1}}$, or Jy · ms). Notice that Equation (9) is different from the formula used in some previous influential papers including the FRB catalog paper (Caleb et al. 2016; Petroff et al. 2016) in two aspects. First, we use the central frequency ν_c, rather than the bandwidth B of the telescope, to derive L_p and E. We believe that this is more appropriate. Bandwidth B makes a connection between the detected energy and fluence, but for estimating the source energy, one should use the central frequency ν_c. Let us consider the same FRB detected by two telescopes with the same ν_c but different bandwidths B. The telescope with a wider band receives more energy than the one with a narrower band, but their derived specific flux (energy per unit frequency per unit time per unit area) should be the same. When one estimates the luminosity and energy of the source, the formula of Petroff et al. (2016), Caleb et al. (2016) would give two different values for the same source, which is apparently incorrect. One may also consider two telescopes with the same B but operating at two different ν_c values. If these two telescopes each detected an FRB with the same specific flux/fluence, using the formula of Petroff et al. (2016), Caleb et al. (2016) would give rise to the same L_p and E for the two FRBs, while in reality the burst detected in the higher frequency band should have higher L_p and E than the other one. Therefore, using ν_c to calculate L_p and E is more reasonable. Second, the factor $(1+z)$ was

[3] In principle, $f_{\rm IGM}$ can be redshift-dependent. Here we adopt an average value by assuming that the redshift evolution effect is not significant.

Table 1
Observational Properties of a Sample of FRBs (Including "All Events" in the FRB Catalog as of 2018 August 15, http://www.frbcat.org Petroff et al. 2016) and Their Estimated Average Upper Limits of Redshift (z), Isotropic Peak Luminosity (L_p), and Isotropic Energy (E)

FRB Name (yymmdd)	DM (pc cm^{-3})	DM$_E$ (pc cm^{-3})	z	$S_{\nu,p}$ (Jy)	t_{obs} (ms)	ν_c[a] (MHz)	L_p (10^{43} erg/s)	E (10^{40} erg)	Telescope	S/N
FRB 010125	790 ± 3	680	<0.76	0.3	9.4	1372.5	<1.16	<6.22	Parkes	17
FRB 010621[b]	745 ± 10	222	<0.26	0.41	7	1374	<0.124	<0.691	Parkes	16.3
FRB 010724	375	330.42	<0.38	30	5	1374	<21.9	<79.3	Parkes	23
FRB 090625	899.55 ± 0.01	867.86	<0.97	1.14	1.92	1352	<11.7	<11.4	Parkes	30
FRB 110220	944.38 ± 0.05	909.61	<1.01	1.3	5.6	1352	<18.6	<51.8	Parkes	49
FRB 110523	623.3 ± 0.06	579.78	<0.65	0.6	1.73	800	<0.928	<0.972	GBT	42
FRB 110626	723 ± 0.3	675.54	<0.76	0.4	1.4	1352	<1.53	<1.22	Parkes	11
FRB 110703	1103.6 ± 0.7	1071.27	<1.19	0.5	4.3	1352	<5.74	<11.3	Parkes	16
FRB 120127	553.3 ± 0.3	521.48	<0.59	0.5	1.1	1352	<1.03	<0.711	Parkes	11
FRB 121002	1629.18 ± 0.02	1554.91	<1.75	0.43	5.44	1352	<12.7	<25.1	Parkes	16
FRB 121102	557 ± 2	369	<0.42	0.4	3	1375	<0.370	<0.782	Arecibo	14
FRB 130626	952.4 ± 0.1	885.53	<0.99	0.74	1.98	1352	<5.39	<5.36	Parkes	21
FRB 130628	469.88 ± 0.01	417.3	<0.48	1.91	0.64	1352	<2.38	<1.03	Parkes	29
FRB 130729	861 ± 2	830	<0.92	0.22	15.61	1352	<1.34	<10.9	Parkes	14
FRB 131104	779 ± 1	707.9	<0.79	1.12	2.08	1352	<4.69	<5.45	Parkes	30
FRB 140514	562.7 ± 0.6	527.8	<0.60	0.471	2.8	1352	<1.00	<1.76	Parkes	16
FRB 150215	1105.6 ± 0.8	678.4	<0.76	0.7	2.88	1352	<2.68	<4.38	Parkes	19
FRB 150418	776.2 ± 0.5	587.7	<0.66	2.2	0.8	1352	<5.93	<2.85	Parkes	39
FRB 150610	1593.9 ± 0.6	1471.9	<1.65	0.7	2	1352	<17.9	<13.5	Parkes	18
FRB 150807	266.5 ± 0.1	229.6	<0.27	128	0.35	1352	<41.7	<11.5	Parkes	0[c]
FRB 151206	1909.8 ± 0.6	1749.8	<1.99	0.3	3	1352	<12.1	<12.2	Parkes	10
FRB 151230	960.4 ± 0.5	922.4	<1.03	0.42	4.4	1352	<3.36	<7.28	Parkes	17
FRB 160102	2596.1 ± 0.3	2583.1	<3.10	0.5	3.4	1352	<59.2	<49.1	Parkes	16
FRB 160317	1165 ± 11	845.4	<0.94	3	21	843	<12.0	<129	UTMOST	13
FRB 160410	278 ± 3	220.3	<0.26	7	4	843	<1.30	<4.13	UTMOST	13
FRB 160608	682 ± 7	443.7	<0.50	4.3	9	843	<3.69	<22.1	UTMOST	12
FRB 170107	609.5 ± 0.5	574.5	<0.65	22.3	2.6	1320	<56.9	<89.6	ASKAP	16
FRB 170827	176.4 ± 0	139.4	<0.17	50.3	0.4	835	<3.57	<1.22	UTMOST	90
FRB 170922	1111	1066	<1.19	2.3	26	835	<16.3	<194	UTMOST	22
FRB 171209	1458	1445	<1.62	0.92	2.5	1352	<22.6	<21.5	Parkes	40
FRB 180301	520	365	<0.42	0.5	3	1352	<0.455	<0.962	Parkes	16
FRB 180309	263.47	218.78	<0.26	20.8	0.576	1352	<6.20	<2.84	Parkes	411
FRB 180311	1575.6	1530.4	<1.72	0.2	12	1352	<5.68	<25.1	Parkes	11.5
FRB 180528	899	830	<0.92	13.8	1.3	835	<51.7	<35.0	UTMOST	14
FRB 180714	1469.873	1212.873	<1.35	5	1	1352	<78.0	<33.2	Parkes	20
FRB 180725A[d]	716.6	647.6	<0.73		2	600			CHIME	20.6

Notes.
[a] Notice that ν_c can be different for the same telescope. The values presented are the ones reported in the original discovery papers.
[b] This FRB reached saturation so that the peak flux and S/N reported (Lorimer et al. 2007) was greatly underestimated.
[c] No S/N was reported in the original paper (Ravi et al. 2016).
[d] No flux was reported in the original ATel (Boyle 2018).

applied incorrectly in those papers when connecting specific fluence with the FRB energy.[4] The definition of luminosity distance D_L is such that the luminosity L (in units of erg s^{-1}) and flux S (in units of erg s^{-1} cm^{-2} or Jy Hz) are connected through $L = 4\pi D_L^2 S$. When this is multiplied by the burst-frame intrinsic time $\tau = \tau_{obs}/(1+z)$ the result is energy, which is Equation (9); note $S\tau_{obs} = \mathcal{F} = \mathcal{F}_\nu \nu_c$, where $\mathcal{F}$ is the fluence (in units of erg cm^{-2} or Jy ms Hz).

The results are presented in Table 1. Without knowing DM$_{host}$ and DM$_{src}$ and their distributions, one can only present the upper limits of z, L_p and E. As there are line-of-sight fluctuations (McQuinn 2014), one can only present the average values.

For the FRB sample published in the FRB Catalogue (FRBCAT) so far, the average z upper limit ranges from 0.17 (FRB 170827; Farah et al. 2017b) to 3.10 (FRB 160102; Bhandari et al. 2018). The average isotropic peak luminosity L_p upper limit ranges from 1.24×10^{42} erg s^{-1} (FRB 010621; Keane et al. 2012) to 7.80×10^{44} erg s^{-1} (FRB 180714; Oslowski et al. 2018) with a spread of 2.80 dex. The average isotropic energy E upper limit ranges from 6.91×10^{39} erg (FRB 010621) to 1.94×10^{42} erg (FRB 170922; Farah et al. 2017a) with a spread of 2.45 dex.

3. Detectability of High-z FRBs

With the Parkes telescope, an FRB with an average redshift upper limit $z \sim 3.10$ was already detected (FRB 160102 with DM$_E \sim 2583$ pc cm^{-3}). This burst has the second-highest average L_p upper limit (5.69×10^{44} erg s^{-1}) and has a

[4] According to Equation (2) of Petroff et al. (2016) and Equation (2) of Caleb et al. (2016), one has $E = 4\pi D_L^2(1+z)\mathcal{F}_\nu B$, with the $(1+z)$ factor in the numerator rather than in the denominator.

signal-to-noise ratio (S/N) 16 at Parkes, which means that it may be detectable at an even higher redshift.

To investigate from how high of a redshift a particular FRB can be detected, one needs to make the assumptions about $\mathrm{DM_{host}} + \mathrm{DM_{src}}$ and the spectral shape of the FRB. Observationally, the two DM terms are coupled and not easy to differentiate, even though the information of rotation measure may help to break the degeneracy (Caleb et al. 2018). The host component $\mathrm{DM_{host}}$ has been studied based on the observations of different types of galaxies (e.g., Xu & Han 2015; Luo et al. 2018). The typical value is a few tens $\mathrm{pc \cdot cm^{-3}}$. The source component $\mathrm{DM_{src}}$ depends on FRB progenitor models, and it can be large for some models that invoke a dense circumburst medium such as a supernova remnant (e.g., Murase et al. 2016; Piro 2016; Metzger et al. 2017; Yang & Zhang 2017). A relatively large value of $\mathrm{DM_{host}} + \mathrm{DM_{src}}$ was inferred for FRB 121102 (Tendulkar et al. 2017) and from a statistical analysis (Yang et al. 2017). To balance different considerations, we assume that the intrinsic value of $\mathrm{DM_{host}} + \mathrm{DM_{src}} \sim 100\,\mathrm{pc \cdot cm^{-3}}$. The observed value of this sum is smaller by a factor of $(1 + z)$.[5]

Let us consider an FRB with the observed peak specific flux $S_{\nu,p}$, duration $\tau_{\rm obs}$, and redshift z. Now imagine that this FRB is moved to a higher redshift z': its peak specific flux $S'_{\nu,p}$ in the same observational frequency band can be calculated as

$$S'_{\nu,p} = \frac{kL_p}{4\pi(D'_{\rm L})^2\nu_c}\frac{\hat{\tau}_{\rm obs}}{\hat{\tau}'_{\rm obs}} = kS_{\nu,p}\left(\frac{D_{\rm L}}{D'_{\rm L}}\right)^2\frac{\hat{\tau}_{\rm obs}}{\hat{\tau}'_{\rm obs}}, \tag{10}$$

where $\hat{\tau}_{\rm obs} = \tau_{\rm obs}/(1+z)$, $\hat{\tau}'_{\rm obs} = \tau'_{\rm obs}/(1+z')$ are cosmological-frame equivalence of the observed duration, and

$$k = \frac{\int_{\nu_a(1+z')}^{\nu_b(1+z')} L_\nu d\nu}{\int_{\nu_a(1+z)}^{\nu_b(1+z)} L_\nu d\nu} = \left(\frac{1+z'}{1+z}\right)^{1-\alpha} \tag{11}$$

is the k-correction factor, with (ν_a, ν_b) denoting the frequency range of the observational band (with central frequency ν_c). The right-most term of Equation (11) has applied the assumption of a power law FRB spectrum, i.e., $L_\nu \propto \nu^{-\alpha}$.

The observed FRB duration (also called width in the literature) may be written as

$$\tau_{\rm obs} = (\tau_{\rm int}^2(1+z)^2 + \tau_{\rm scat}^2 + \tau_{\rm ins}^2)^{1/2}, \tag{12}$$

where $\tau_{\rm int}$ is the intrinsic duration of the FRB in the cosmological frame,

$$\tau_{\rm scat} = (\tau_{\rm MW}^2 + \tau_{\rm IGM}^2 + \tau_{\rm host}^2(1+z)^2)^2 \tag{13}$$

is the duration due to plasma scattering, which includes contributions from the Milky Way (MW), IGM, and the host (including the host galaxy and the immediate environment of the FRB source), and

$$\tau_{\rm ins} = (\tau_{\rm DM}^2 + \tau_{\delta \rm DM}^2 + \tau_{\delta\nu}^2 + \tau_{\rm samp}^2)^2 \tag{14}$$

is the instrument-related duration (Cordes & McLaughlin 2003; Caleb et al. 2016), where

$$\tau_{\rm DM} = 8.3\mu{\rm s}\ {\rm DM}\Delta\nu_{\rm MHz}\nu_{\rm GHz}^{-3} \tag{15}$$

is the frequency-dependent smearing due to dispersion measure, $\tau_\delta{\rm DM} = \tau_{\rm DM}(\delta{\rm DM}/{\rm DM})$ is the smearing due to the error of DM, $\tau_\nu \sim (\Delta\nu)^{-1} = 1\,\mu{\rm s}\,(\Delta\nu_{\rm MHz})^{-1}$ is the smearing due to the bandwidth, and $\tau_{\rm samp}$ is the sampling time (which is typically $>50\,\mu$s for most telescopes but is in any case <1 ms). Putting everything together, one can write

$$\hat{\tau}_{\rm obs} = \frac{\tau_{\rm obs}}{1+z} = \left[\tau_{\rm int}^2 + \tau_{\rm host}^2 + \frac{\tau_{\rm MW}^2 + \tau_{\rm IGM}^2 + \tau_{\rm DM}^2 + \tau_{\delta \rm DM}^2 + \tau_{\delta\nu}^2 + \tau_{\rm samp}^2}{(1+z)^2}\right]^{1/2}. \tag{16}$$

In the following, we argue that for FRBs with $z > 2$, $\hat{\tau}_{\rm obs}$ essentially does not vary when the same FRB is moved to higher redshifts. Out of the many terms that determine the observed duration (width) $\tau_{\rm obs}$, three terms likely dominate: the intrinsic duration $\tau_{\rm int}$ as is the case of the repeater (Spitler et al. 2016), the scattering tail term $\tau_{\rm scat}$ as is the case of the Lorimer burst (Lorimer et al. 2007), as well as the DM smearing term when either of the first two terms is negligibly small. For the three scattering terms, because FRBs are from high Galactic altitudes, $\mathrm{DM_{MW}}$ is negligibly small. Between the contributions from the IGM and host, Xu & Zhang (2016) showed that the former is negligibly small for typical turbulent properties of the IGM and that the latter can be the dominant term. The negligible scattering from the IGM is also evident from the fact that there is no clear correlation between the observed width and DM for FRBs. As a result, the dominant terms in Equation (16) are $\tau_{\rm int}^2$, $\tau_{\rm host}^2$, which do not depend on z; and $(\tau_{\rm DM}/(1+z))^2$, which is $\propto({\rm DM}/(1+z))^2$. At a high redshift, DM is dominated by the IGM term. If one neglects the small corrections due to the change of ionization factors as a function of redshift (i.e., $\mathrm{DM_{IGM}} \propto F(z)$, Equation (6)), the function $\mathrm{DM_{IGM}}/(1+z) \propto F(z)/(1+z)$ initially rises, reaching a peak around $z \sim 4$, and decays at higher z. In the redshift range from $z = 2$ to $z = 10$, $\mathrm{DM_{IGM}}/(1+z)$ is essentially constant within 5% error. As a result, the DM smearing effect is equivalent to the cosmological time dilation effect. At even higher redshifts (e.g., $z > 10$), $\mathrm{DM_{IGM}}/(1+z)$ steadily declines, so that the DM smearing cannot compensate for the $(1+z)$ stretching, and $\hat{\tau}_{\rm obs}$ starts to slowly decrease with an increasing z. As $\chi_{\rm e,He}$ starts to become less than 1 at $z > 3$ (Zheng et al. 2014) and $\chi_{\rm e,H}$ starts to become less than 1 at $z > 6$ (Fan et al. 2006), this effect is further enhanced if a precise treatment of ionization is conducted.

Finally, in principle there could be a "tip-of-iceberg" effect similar to other transients such as GRBs (e.g., Lü et al. 2014), i.e., the same burst would have a longer duration if it is detected with a more sensitive telescope, because more emission is observed above the background noise. In principle, $\hat{\tau}_{\rm obs}$ may be shorter than its true value at a higher redshift, because the S/N drops when z increases. However, for rapidly variable transients such as FRBs, both rising and decaying slopes are very steep, meaning that this effect may be negligible.

[5] For a larger value of $\mathrm{DM_{host}} + \mathrm{DM_{src}}$, as suggested by FRB 121102, the estimates to z, L_p, and E for nearby events would be smaller (and more uncertain), but our discussion about the high-z FRBs is not significantly affected due to the $(1 + z)$ suppression factor.

Taking $\hat{\tau}_{\rm obs} \simeq \hat{\tau}'_{\rm obs}$ and combining Equations (10) and (11), one finally gets

$$S'_{\nu,p} \simeq S_{\nu,p} k \left(\frac{D_{\rm L}}{D'_{\rm L}}\right)^2 \simeq S_{\nu,p} \left(\frac{D_{\rm L}}{D'_{\rm L}}\right)^2 \left(\frac{1+z'}{1+z}\right)^{1-\alpha}. \quad (17)$$

One can see that there are two effects that directly reduce the peak flux of an FRB as it is moved to a higher redshift: the increase of the luminosity distance, and the negative k-correction (i.e., one is looking at an intrinsically higher frequency in the source frame where the flux is lower due to the power-law spectrum given the same observational frequency). The latter applies to the majority of FRBs, but if the spectral slope of an FRB is positive (e.g., some bursts from the repeater Scholz et al. 2016; Spitler et al. 2016; Law et al. 2017), k-correction can be actually positive.

With the above preparation, one may discuss from how far away the current FRBs can be detected. We consider two FRBs with the highest L_p upper limits: FRB 160102 with $\rm DM_E = 2583.1\ pc\ cm^{-3}$ (Caleb et al. 2018, L_p upper limit $5.92 \times 10^{44}\ \rm erg\ s^{-1}$) and FRB 180714 with $\rm DM_E = 1212.873\ pc\ cm^{-3}$ (Petroff et al. 2016, L_p upper limit $7.80 \times 10^{44}\ \rm erg\ s^{-1}$). Both were detected by Parkes, with the S/N 16 and 20, respectively. The spectral indices of FRBs are poorly constrained. We take a typical value $\alpha \sim 1.6$ for radio pulsars (e.g., Lorimer et al. 1995; Xilouris et al. 1996; Jankowski et al. 2018), which is also consistent with the theoretical prediction of coherent curvature radiation by bunches (Yang & Zhang 2018). Taking S/N = 10 as the threshold for detection and assuming $\rm DM_{host} + DM_{src} \sim 100\ pc \cdot cm^{-3}$ for both events, one can perform the following estimates:[6] FRB 160102 is at $z \sim 3.06$ with $\rm DM_{IGM} \sim 2556\ pc\ cm^{-3}$ and $L_p \sim 5.74 \times 10^{44}\ \rm erg\ s^{-1}$. To reduce the S/N from 16 to 10, the burst can be detected by Parkes up to $z \sim 3.61$ with $\rm DM_{IGM} \sim 2934\ pc\ cm^{-3}$ and a total observed DM $\sim 2947\ \rm pc\ cm^{-3}$. FRB 180714 is at $z \sim 1.30$ with $\rm DM_{IGM} \sim 1170\ pc\ cm^{-3}$ and $L_p \sim 7.12 \times 10^{44}\ \rm erg\ s^{-1}$. To reduce the S/N from 20 to 10, the burst can be detected by Parkes up to $z \sim 1.66$ with $\rm DM_{IGM} \sim 1477\ pc\ cm^{-3}$ and total observed DM $\sim 1877\ \rm pc\ cm^{-3}$. FRB 160102 has a lower peak luminosity but is detected at a higher redshift than FRB 180714. This is probably because it was detected at a more favorable beam angle.

Telescopes with larger apertures (and hence, higher sensitivities), e.g., the 300 m Arecibo Radio Telescope and FAST, will have a better chance to detect FRBs at even higher redshifts. By design, FAST has an effective area $A_{\rm eff} = 50{,}000\ \rm m^2$ and system temperature $T_{\rm sys} = 25$ K (Li et al. 2018a). Compared with the effective area $A_{\rm eff} = 0.6\pi\ (64/2)^2 = 1930\ \rm m^2$ and system temperature $T_{\rm sys} = 24$ K (Staveley-Smith et al. 1996), the sensitivity of FAST (characterized by $A_{\rm eff}/T_{\rm sys}$) is about 25 times of that of Parkes. To be more conservative, in the following we perform the estimate by assuming that FAST is 20 times more sensitive than Parkes. Again consider FRB 160102. FAST would have detected it with an S/N $\sim$320. To reduce the S/N from 320 to 10, the burst can be detected at $z \sim 10.4$ with $\rm DM_{IGM} \sim 6487\ pc\ cm^{-3}$ and a total observed DM $\sim 6500\ \rm pc\ cm^{-3}$ for $\alpha = 1.6$. Here we have not considered the fact that both He and H are partially ionized at such a high redshift, so that the estimated free electron column density, and therefore $\rm DM_{IGM}$, is an upper limit.

If there exist FRBs at even higher redshifts with even higher luminosities, large telescopes such as FAST may be still able to barely detect them. It would be interesting to estimate the DM value of these events to optimize the search strategy. For $z \sim 15$, the IGM DM value according to Equation (3) sets an upper limit $\rm DM_{IGM} < 8295\ pc\ cm^{-3}$. IGM is nearly neutral at such a high redshift, so the real $\rm DM_{IGM}$ should be much smaller. Even if one assigns a large $\rm DM_{MW} \sim 1000\ pc\ cm^{-3}$ to reflect their possible low Galactic latitudes, the maximum observed DM may be close to, but not exceeding, $9000\ \rm pc\ cm^{-3}$ (the contributions from the host and source is greatly reduced due to the large reduction by a factor $(1+z) \sim 16$, and $\rm DM_{IGM}$ is much smaller than what Equation (3) presents, because $\chi_{e,\rm H}$ and $\chi_{e,\rm He}$ are less than unity at such high redshifts; see also Fialkov & Loeb 2016). As a result, the upper limit DM for FAST FRB search may be set to[7] $9000\ \rm pc\ cm^{-3}$.

For radio telescopes, the collecting area A and the beam solid angle $\Delta\Omega$ satisfies $A \cdot \Delta\Omega \sim$ const. In an Euclidean geometry with an isotropic distribution of the sources, the horizon distance scales as $D_h \propto S_{\rm th}^{-1/2} \propto A^{1/2}$ (where $S_{\rm th}$ is the threshold flux above which the source is detectable). Assuming a uniform source event rate density $\dot{n}$ (number per unit time per unit volume) for a certain type of transient, the total detection rate (number per unit time) scales as $\dot{N} \propto \dot{n} V_{\rm horizon} \Delta\Omega \propto \dot{n} D_h^3 \Delta\Omega \propto \dot{n} A^{3/2} A^{-1} \propto \dot{n} A^{1/2}$. For a constant $\dot{n}$, the detection rate would scale up with an increasing telescope aperture. For cosmological sources such as FRBs, on the other hand, D_h should be replaced by $D_{\rm L,h}$, which still satisfies $D_{\rm L,h} \propto S_{\rm th}^{-1/2} \propto A^{1/2}$. However, the horizon volume increases much more slowly than $D_{\rm L}^3$. In general, the detected event rate by a telescope can be written as

$$\dot{N} = \Delta\Omega \int_0^{z_h} dz \frac{dV(z)}{dz} \frac{\dot{n}_{\rm FRB}(z)}{1+z} \int_{L_{\rm th}(z)}^{L_{\rm max}} \phi(L') dL', \quad (18)$$

where $\phi(L')dL' \propto L'^{-\alpha_{\rm L}} dL'$ is the FRB luminosity function,[8]

$$\frac{dV}{dz} = \frac{c}{H_0} \frac{D_{\rm L}^2(z)}{(1+z)^2 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \quad (19)$$

is the redshift-dependent cosmological volume in ΛCDM cosmology, and $\dot{n}_{\rm FRB}(z)$ is the event rate density at redshift z. At large redshifts, the horizon volume increase is negligible, so that the increase of $\dot{N}$ is mostly due to the increase of $\int_{L_{\rm th}(z)}^{L_{\rm max}} \phi(L')dL'$. Given a same z (and $D_{\rm L}$), one has $L_{\rm th} \propto S_{\rm th} \propto A^{-1}$, so that $\dot{N} \propto \Delta\Omega \int_{L_{\rm th}}^{L_{\rm max}} \phi(L')dL' \propto \Delta\Omega L_{\rm th}^{1-\alpha_{\rm L}} \propto A^{\alpha_{\rm L}-2}$. The luminosity function of FRBs is poorly constrained with the current data (e.g., Caleb et al. 2016; Li et al. 2017). If one adopts $\alpha_{\rm L} \sim 2$, a typical value for cosmological transients (Sun et al. 2015), then the

6 Here $\rm DM_{IGM}$ is precisely adopted as the average value, and full ionization of He and H have been assumed. In reality, line-of-sight variations of $\rm DM_{IGM}$ would introduce a large error to render the estimated numbers less precise. Other factors, such as the unknown $\rm DM_{host} + DM_{src}$ value and the source direction from the telescope observing beam, would introduce further uncertainties in the estimates.

7 If FRBs with DM $> 9000\ \rm pc\ cm^{-3}$ are indeed detected by any current radio telescope, they should have a huge DM contribution from the host/source (say, $\rm DM_{host} + DM_{src} > 8000\ pc\ cm^{-3}$) but at a very low redshift (say, $z < 0.5$).

8 The luminosity function discussed here refers to that in an observational band, which is observational tractable. The bolometric luminosity function may be more intrinsic, but observationally it is difficult to constrain. The power-law index of the bolometric luminosity function would be related to $\alpha_{\rm L}$ through the spectral index α as well as the relationship between the bolometric luminosity and the peak frequency of FRBs.

dependence on A disappears. As a result, large telescopes such as FAST may have a detection rate comparable to smaller telescopes such as Parkes. More generally, large-aperture telescopes tend to detect more FRBs if α_L is steeper than 2, and vice versa. In any case, the majority of FRBs detected by larger-aperture radio telescopes should be still nearby low-luminosity ones. Only a small fraction may be high-z FRBs not detectable by smaller telescopes.

4. Summary

In view that at least FRB 121102 is cosmological and that many more FRBs will be detected with current and upcoming radio telescopes, here we study the cosmological aspect of FRBs with the focus on the FRB energetics and the prospects of detecting high-z FRBs. Our main conclusions can be summarized as follows.

1. Adopting a more precise $DM_{IGM} - z$ relation (Deng & Zhang 2014), the estimated average redshift upper limit of an FRB for a given DM_E is higher (Table 1). A more precise estimate of the average z upper limit, i.e., $z \sim DM_E/855\,pc\,cm^{-3}$ instead of $z \sim DM_E/1200\,pc\,cm^{-3}$, is recommended. As there are line-of-sight fluctuations due to large-scale structures (McQuinn 2014), the upper limit redshift falls in the range from $DM_E/510\,pc\,cm^{-3}$ to $DM_E/1200\,pc\,cm^{-3}$.
2. The isotropic peak luminosity and energy in the observed band of an FRB can be estimated using Equations (8) and (9). The $(1+z)$ factor was misused in the expression of E in some previous papers. The central frequency ν_c, rather than the bandwidth B, should be used in these calculations.
3. Considering various terms contributing to the observed duration (width) of the FRB pulses, one can draw the conclusion that the cosmological restframe equivalent duration $\hat{\tau}_{obs} = \tau_{obs}/(1+z)$ is essentially constant regardless of whether the duration is dominated by intrinsic duration, host galaxy/source scattering, or DM smearing. The DM smearing effect is comparable to the time dilation effect.
4. One may estimate the peak flux of a pseudo FRB using Equation (17) when a known FRB is moved to a higher redshift.
5. In the current sample, FRB 160102 with $DM = 2596.1 \pm 0.3\,pc\,cm^{-3}$ likely has the highest redshift. Assuming $DM_{host} + DM_{scr} \sim 100\,pc\,cm^{-3}$, this FRB has a peak luminosity $L_p \sim 5.74 \times 10^{44}\,erg\,s^{-1}$, which can be in principle detected up to $z \sim 3.61$ by Parkes with an observed $DM \sim 2947\,pc\,cm^{-3}$, and by FAST under ideal conditions up to $z \sim 10.4$ with an observed $DM \sim 6500\,pc\,cm^{-3}$.
6. Assuming that FRBs detectable up to $z \sim 15$ do exist, the upper limit DM for FRB searches may be set to $\sim 9000\,pc\,cm^{-3}$ for sensitive radio telescopes such as FAST.
7. For single-dish telescopes, those with a larger aperture tend to detect more FRBs than those with a smaller aperture if the FRB luminosity function index α_L is steeper than 2, and vice versa. Even though small telescope arrays (e.g., CHIME, ASKAP, MeerKAT) will detect and localize many more FRBs, large-aperture telescopes such as FAST are more capable of detecting high-z FRBs.

Finally, we would like to stress that detecting high-z FRBs with large-aperture telescopes is very important scientifically. If these sources can be localized so that a secure redshift z is measured, DM_E can be applied to perform unique studies. At high redshifts, $DM_E \sim DM_{IGM}$, and DM_{IGM} fluctuation is significantly reduced. One can then investigate how much $\chi_{e,H}$ and $\chi_{e,He}$ deviate from unity in Equation (4), so that the state of reionization in the IGM can be probed directly.

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References

Amiri, M., Bandura, K., Berger, P., et al. 2018, ApJ, 863, 48
Bailes, M., Jameson, A., Flynn, C., et al. 2017, PASA, 34, e045
Bhandari, S., Keane, E. F., Barr, E. D., et al. 2018, MNRAS, 475, 1427
Booth, R. S., de Blok, W. J. G., Jonas, J. L., & Fanaroff, B. 2009, arXiv:0910.2935
Boyle, P. J. & Chime/Frb Collaboration 2018, ATel, 11901, 1
Caleb, M., Flynn, C., Bailes, M., et al. 2016, MNRAS, 458, 708
Caleb, M., Keane, E. F., van Straten, W., et al. 2018, MNRAS, 478, 2046
Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Natur, 541, 58
Connor, L., Sievers, J., & Pen, U.-L. 2016, MNRAS, 458, L19
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Cordes, J. M., & McLaughlin, M. A. 2003, ApJ, 596, 1142
Cordes, J. M., & Wasserman, I. 2016, MNRAS, 457, 232
Cucchiara, A., Levan, A. J., Fox, D. B., et al. 2011, ApJ, 736, 7
Deng, W., & Zhang, B. 2014, ApJL, 783, L35
Dolag, K., Gaensler, B. M., Beck, A. M., & Beck, M. C. 2015, MNRAS, 451, 4277
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Farah, W., Bailes, M., Jameson, A., et al. 2017a, ATel, 10867, 1
Farah, W., Flynn, C., Jameson, A., et al. 2017b, ATel, 10697, 1
Fialkov, A., & Loeb, A. 2016, JCAP, 5, 004
Fialkov, A., & Loeb, A. 2017, ApJL, 846, L27
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518
Gao, H., Li, Z., & Zhang, B. 2014, ApJ, 788, 189
Inoue, S. 2004, MNRAS, 348, 999
Ioka, K. 2003, ApJL, 598, L79
Jankowski, F., van Straten, W., Keane, E. F., et al. 2018, MNRAS, 473, 4436
Johnston, S., Feain, I. J., & Gupta, N. 2009, in ASP Conf. Ser. 407, The Low-Frequency Radio Universe, ed. D. J. Saikia et al. (San Francisco, CA: ASP), 446
Katz, J. I. 2018, arXiv:1804.09092
Keane, E. F., Johnston, S., Bhandari, S., et al. 2016, Natur, 530, 453
Keane, E. F., Stappers, B. W., Kramer, M., & Lyne, A. G. 2012, MNRAS, 425, L71
Law, C. J., Abruzzo, M. W., Bassa, C. G., et al. 2017, ApJ, 850, 76
Li, D., Wang, P., Qian, L., et al. 2018a, IMMag, 19, 112
Li, L.-B., Huang, Y.-F., Zhang, Z.-B., Li, D., & Li, B. 2017, RAA, 17, 6
Li, Z., Gao, H., Ding, X.-H., Wang, G.-J., & Zhang, B. 2018b, NatCo, 9, 3933
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Sci, 318, 777
Lorimer, D. R., Yates, J. A., Lyne, A. G., & Gould, D. M. 1995, MNRAS, 273, 411
Lü, H.-J., Zhang, B., Liang, E.-W., Zhang, B.-B., & Sakamoto, T. 2014, MNRAS, 442, 1922

Luo, R., Lee, K., Lorimer, D. R., & Zhang, B. 2018, MNRAS, 481, 2320
Macquart, J.-P., & Ekers, R. 2018, MNRAS, 480, 4211
Macquart, J. P., Keane, E., Grainge, K., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), ed. T. L. Bourke et al. (Trieste: Sissa), 55
Marcote, B., Paragi, Z., Hessels, J. W. T., et al. 2017, ApJL, 834, L8
McQuinn, M. 2014, ApJL, 780, L33
Metzger, B. D., Berger, E., & Margalit, B. 2017, ApJ, 841, 14
Murase, K., Kashiyama, K., & Mészáros, P. 2016, MNRAS, 461, 1498
Oslowski, S., Shannon, R. M., Jameson, A., et al. 2018, ATel, 11851, 1
Petroff, E., Barr, E. D., Jameson, A., et al. 2016, PASA, 33, e045
Petroff, E., Johnston, S., Keane, E. F., et al. 2015, MNRAS, 454, 457
Piro, A. L. 2016, ApJL, 824, L32
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13
Ravi, V., Shannon, R. M., Bailes, M., et al. 2016, Sci, 354, 1249
Scholz, P., Spitler, L. G., Hessels, J. W. T., et al. 2016, ApJ, 833, 177
Shao, L., & Zhang, B. 2017, PhRvD, 95, 123010
Spitler, L. G., Scholz, P., Hessels, J. W. T., et al. 2016, Natur, 531, 202
Staveley-Smith, L., Wilson, W. E., Bird, T. S., et al. 1996, PASA, 13, 243
Sun, H., Zhang, B., & Li, Z. 2015, ApJ, 812, 33
Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, ApJL, 834, L7
Thornton, D., Stappers, B., Bailes, M., et al. 2013, Sci, 341, 53
Walters, A., Weltman, A., Gaensler, B. M., Ma, Y.-Z., & Witzemann, A. 2018, ApJ, 856, 65
Wei, J.-J., Gao, H., Wu, X.-F., & Mészáros, P. 2015, PhRvL, 115, 261101
Wu, X.-F., Zhang, S.-B., Gao, H., et al. 2016, ApJL, 822, L15
Xilouris, K. M., Kramer, M., Jessner, A., Wielebinski, R., & Timofeev, M. 1996, A&A, 309, 481
Xu, J., & Han, J. L. 2015, RAA, 15, 1629
Xu, S., & Zhang, B. 2016, ApJ, 832, 199
Yang, Y.-P., Luo, R., Li, Z., & Zhang, B. 2017, ApJL, 839, L25
Yang, Y.-P., & Zhang, B. 2016, ApJL, 830, L31
Yang, Y.-P., & Zhang, B. 2017, ApJ, 847, 22
Yang, Y.-P., & Zhang, B. 2018, ApJ, in press (arXiv:1712.02702)
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Zhang, B. 2014, ApJL, 780, L21
Zheng, Z., Ofek, E. O., Kulkarni, S. R., Neill, J. D., & Juric, M. 2014, ApJ, 797, 71
Zhou, B., Li, X., Wang, T., Fan, Y.-Z., & Wei, D.-M. 2014, PhRvD, 89, 107303