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Host Galaxy Dispersion Measure of Fast Radio Burst

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ABSTRACT

Fast radio bursts are a class of transient radio sources that are thought to originate from extragalactic sources since their dispersion measure greatly exceeds the highest dispersion measure that the Milky Way interstellar medium can provide. Host Galaxies of twenty-two fast radio bursts have already been identified [1]. In this paper, the dispersion measurement of these fast radio bursts produced by the Milky Way interstellar medium, and the intergalactic medium is obtained through known physical models to yield the host galaxy dispersion measure. It is observed that the host galaxy dispersion measure increases with its redshift value. We also obtained that the host galaxy dispersion measure has different distribution between repeaters and non-repeaters. It is noted that the reason for the divergence of the host galaxy dispersion measures should be accounted for by the difference in their local environment.

KEYWORDS: *Fast radio burst, Host galaxy, Dispersion measure*

INTRODUCTION

Fast Radio Burst (FRB) is a kind of radio transient with typical duration of several milliseconds and usually brighter than 1 Jy ms. Since the discovery of the first FRB [2], hundreds of FRB events have been detected [3, 4], which are divided into repeating and non- repeating bursts. The difference in their origin is currently undetermined since we cannot conclude whether non-repeaters are also potential candidates for repeaters or not. Thus, although numerous of theoretical models have been proposed for FRB [5], its emission mechanism and physical origin still remains enigmatic. It has been suggested that non- repeating bursts are not unrepeating, but rather that their repeating bursts have not yet been detected, however, some studies argue that the probability that all FRBs are repeating, and the bursts is extremely small [6, 7]. We argue that repeaters and non-repeaters FRBs originate from different physical processes. Repeaters originate from non-catastrophic physical processes, such as giant pulses of young pulsars [8], giant flares of magnetar [9], accretion of white dwarfs by neutron stars [10], etc. whereas Non-repeaters originate from catastrophic events such as the collapse of massive neutron stars into black holes [11], binary neutron star mergers [12], binary white dwarf mergers [13], neutron star-black hole mergers [14] etc.

A key parameter of FRBs is the dispersion measure (DM), which represents the integrated column density of free electrons between the observer and the signal source. Due to the presence of massive intergalactic and interstellar mediums in the space, the signals from FRB will be affected by these mediums as it travels through to the receiver, resulting in a delay in the reception of the low-frequency signal, which leads to the occurrence of dispersion. By comparing with the existing Milky Way electron distribution model, we can firmly indicate that the DM of FRB is greatly higher than the Milky Way DM contribution, indicating that FRB originates at an extragalactic distance.

The DM values originated from Milky Way (DM_{ISM}) can be deduced from existing models. The three most widely used models are TC93 [15], NE2001 [16], and YMW16 [17].

As the FRB is considered to be extragalactic origin, the observed DM of FRB DM_{obs} is modeled as

$$DM_{obs} = DM_{ISM} + DM_{halo} + DM_{IGM} + DM_{host}/(1+z) \qquad (1)$$

where the DM_{ISM}, DM_{halo}, DM_{IGM} and DM_{host} stand for the DM of interstellar medium(ISM), Milky Way halo, intergalactic medium(IGM), and host galaxy, respectively. z is the redshift. DM_{halo} is the contribution of the Milky Way halo to the total dispersion measure, and the range of its value is considered to be 30 pc cm^{-3} [18], 50 − 80 pc cm^{-3} [19], or 43 pc cm^{-3} based on the YT2020 Milky Way halo model [20].

Since FRBs are identified as extragalactic sources, they should be located in their own host galaxies. Finding the host galaxies of the FRBs therefore becomes an intriguing topic in the field of radio astronomy. However, there are only 22 FRBs discovered with known host galaxies [21, 22, 23].

The median value of DM contribution from the host galaxy is often considered to be 100 pc cm^{-3} with a presented feature of log-normal distribution if the FRB is located in the galactic disk of a Milky Way-like host galaxy that can be represented by the NE2001 model and has an inclination angle of 60° [24, 25]. However, discrepancy can be caused by many factors. Not only do the angle of the observation, the type of the galaxy, the halo contribution, and the magnitude of the redshift generate deviations in the DM_{host} values, there is another important variable that is also relevant (indicate which variable and how it effects the model).

The DM contribution caused by the local environment of the FRB, also known as DM_{source}, describes the complexity of the environment the FRB is located at. The more intricate the local environment is, the greater the DM it will cause. For example, the FRB that is located in an extreme magneto-ionic environment or co-located with a compact, persistent radio source will have a higher DM_{source} than the FRB located in a tranquil void region in the universe [26, 27]. Therefore, it becomes very important to include the DM_{source} in calculations. In this manuscript, DM_{source} has been included in DM_{host}.

DM_{IGM} is the dispersion measure distribution contribution of the intergalactic medium. Its value can be gained from subtracting DM_{host}, DM_{halo}, and DM_{ISM} from the total DM of FRB. Thus, if we assume that the present-day electron numerical density of the intergalactic medium is uniformly distributed at 1.6 × 10^{-7} m^{-3} [28], DM_{IGM} can be used to estimate the distance of FRB from the observer or vice versa, which means that there are also some models that are able to calculate the DM_{IGM} of the FRBs with known host galaxies and redshift based on the distance [29].

As more and more host galaxies of FRBs are observed, it provides a possibility to study the magnitude and distribution of the dispersion measure of FRB host galaxies. Bai et. al. in [30] tried to investigate DM_{host} with 13 FRBs of known host galaxies. They concluded that DM_{host} is nonlinearly related to the redshift value, and that there may be a linear relationship between DM_{host} of non-repeater and the galaxy metallicity. Lin et. al. in [31] studied 17 FRBs with known host galaxies and found no significant relationship between DM_{host} and host galaxy redshift, mass, star formation rate, and other parameters. However, Lin et. al. in [31], the study did not investigate repeaters and non-repeaters separately.

In this paper, we collected samples of FRBs with identified host galaxies, and derived their host galaxy dispersion measures due to the influence of the Milky Way interstellar medium, Milky Way halo and intergalactic medium from existing models. By analyzing the dispersion measures of the host galaxies of repeaters and non-repeaters, we examined whether there is a difference between the galactic or local environments of these FRBs, thereby analyzing the difference in their physical origin.

MATERIALS AND METHODS (DATA AND ANALYSIS)

We collected 22 FRBs with known host galaxies and information about their host galaxies [4, 21, 22, 23, 32] including the observed dispersion measure (DM^{obs}) and the redshift value (z). We estimated the dispersion measure contribution from the Milky Way interstellar medium (DM_{ISM}), based on the YMW16 galactic electron density model [17], and the dispersion measure contribution from the Galactic Halo (DM_{halo}) based on the YT2020 model [20], as listed in Table 1. In the "Rep" column of the table, the value of 0 denotes that the FRB is a non-repeater, and the value of 1 denotes that it is a repeater; z is the host galaxy redshift value; offset is the projected distance of the FRB from the host galaxy galactic center; R is the effective radius of the host galaxy [33]; SFR is the host galaxy star formation rate; M is the mass of the host galaxy.

Since the host galaxies are known, the distance to the FRBs can be considered as the distance to the host galaxies, and thus the dispersion measure contribution of the intergalactic medium (DM_{IGM}) can be estimated according to to the following equation [29, 30, 31, 34].

Table 1. Parameters of FRBs with known host galaxies.

Name	DM_{obs}	DM_{ISM}	DM_{halo}	Rep	z	offset	R	SFR	M
	pc cm^{-3}	pc cm^{-3}	pc cm^{-3}			kpc	kpc	$M_\odot$ yr^{-1}	$M_\odot$
20121102A	557	287.0788	40.91401	1	0.1927	0.75	2.05	0.15	143000000
20180301A	536	253.9594	38.05757	1	0.3305	10.8	5.8	1.93	2300000000
20180916B	348.8	324.8824	43.07673	1	0.0337	5.46	3.57	0.06	2150000000
20180924B	362.16	27.6485	45.54362	0	0.3214	3.37	2.75	0.88	13200000000
20181030A	103.5	33.05255	31.57422	1	0.0039	0	2.6	0.36	5800000000
20181112A	589	29.0287	45.0438	0	0.4755	1.69	7.19	0.37	3980000000
20190102C	364.545	43.28	46.98819	0	0.2913	2.26	5	0.86	3390000000
20190520B	1204.7	50.24369	69.1571	1	0.241	*	*	0.41	600000000
20190523A	760.8	29.87962	32.39296	0	0.66	27.2	3.28	0.09	61200000000
20190608B	340.05	26.62266	38.89012	0	0.1178	6.52	7.37	0.69	11600000000
20190611B	332.63	43.67048	47.21411	0	0.3778	11.7	2.15	0.27	750000000
20190711A	592.6	42.61163	46.20018	1	0.5217	3.17	2.94	0.42	810000000

20190714A	504.13	31.15956	36.43899	0	0.2365	2.7	3.94	0.65	14200000000
20191001A	507.9	31.08082	46.71377	0	0.234	11.1	5.55	8.06	46400000000
20191228A	297.5	19.92478	36.87967	0	0.2432	5.7	1.78	0.03	5400000000
20200120E	87.82	32.50943	31.12772	1	0.00014	20	3.5	0.6	72000000000
20200430A	380.25	26.07647	42.24145	0	0.1608	1.7	1.64	0.26	2100000000
20200906A	577.8	37.86544	30.16039	0	0.3688	5.9	7.58	0.48	13300000000
20201124A	413.52	196.6219	36.23963	1	0.0979	1.3	*	2.12	16000000000
20210117A	728.95	21.43	35.37	0	0.214	2.8	*	0.014	363078054
20220509G	269.53	52.07	37.7	0	0.0894	*	*	*	*
20220914A	631.29	51.11	36.95	0	0.1139	*	*	*	*

$$DM_{IGM} = \frac{3cH_0\Omega_b f_{IGM}}{8\pi G m_p} \times \int_0^z \frac{\left[\frac{3}{4}y_1\chi_{e,H(z)}+\frac{1}{8}y_2\chi_{e,He(z)}\right](1+z)dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}} \qquad (2)$$

where m_p is the mass of proton, H_0 = 67.36 km $s^{-1}\cdot Mpc^{-1}$ is the current Hubble constant, Ω_b = 0.0493 is the relic density parameter of baryonic matter mass, and f_{IGM} = 0.83 is the percentage of baryonic matter mass in the intergalactic medium. $\frac{3}{4}y_1\chi_{e,H(z)}+\frac{1}{8}y_2\chi_{e,He(z)}$ represents the degree of ionization of the intergalactic medium. Assuming that the proportion of hydrogen in the intergalactic medium is 3/4 and the proportion of helium(4) is 1/4, the coefficient y_1~y_2~1. Assuming complete ionization of the intergalactic medium, the ionization degree of hydrogen $\chi_{e,H(z)}$~1 and that of helium $\chi_{e,He(z)}$~1. Ω_m = 0.315 is the relic density parameter of total matter (baryonic as well as dark matter). Ω_Λ= 0.6911 is the relic density of the dark energy.

The dispersion measure contribution from host galaxy can be calculated from eq. (1) as

$$DM_{host} = (1+z)(DM_{obs}-DM_{ISM}-DM_{halo}-DM_{IGM}) \qquad (3)$$

Upon computation of the DM_{host}, we proceeded to construct a scatter plot denoted as Figure 1, depicting the DM_{host} against the redshift values z in an attempt to find any potential correlations between the two. Notably, within our data set, we identified three FRBs with DM_{host} below 0 due to inherent uncertainties in estimating DM_{ISM}, DM_{halo}, and DM_{IGM}. As can be seen from Fig. 1, there is a tendency for the DM_{host} to increase with the redshift value z, and the relationship can be demonstrated by following equation [35]

$$DM_{host} = A(1+z)^\alpha \qquad (4)$$

where the parameters A and α are

A=188.84±99.39, and α=0.70±1.96.

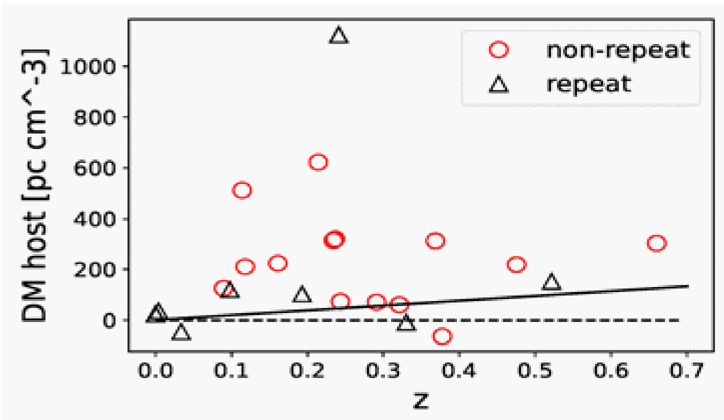

Figure 1. DM_{host} versus redshift z.

The black solid line is the result of the linear fitting of all samples. The black dashed line is the position where the dispersion measure value is 0.

We also noticed from Fig. 1 that the distribution of DM_{host} of repeaters and non-repeaters is different, and repeaters exhibit generally lower DM_{host} compared to non-repeaters. Among them, FRB 20190520B, discovered by the FAST telescope, is a repeater with a significantly higher DM_{host} than other repeaters.

To comprehensively investigate this discrepancy, we conducted an analysis of DM_{host} (samples no less than 0) for repeaters and non-repeaters and plotted histogram for them. The distribution of DM_{host} can be described by a log-normal distribution

[35, 34], so the DM_{host} in the histogram is taken as logarithm with a base of 10, and the result is depicted in Fig. 2. In addition, we fit the histogram with a Gaussian function. The fitted histogram shows that the mean value of non-repeater's DM_{host} is $167.27^{+96.95}_{-61.37}$ pc cm^3 and the repeater's DM_{host} contribution is $111.89^{+315.27}_{-82.58}$pc cm^3.

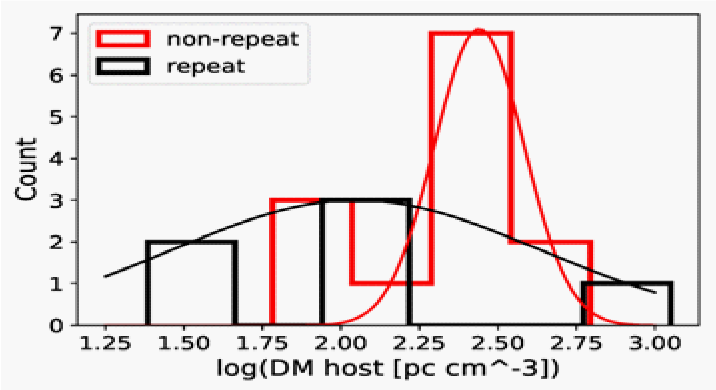

Figure 2. Histogram of the DM_{host}.

The red line is the histogram of non-repeaters. The red curve is the result of its corresponding gaussian function fit. The black line is the histogram of repeaters. The black curve is the result of its corresponding Gaussian fit.

RESULTS AND DISCUSSION

As seen in Fig. 1, DM_{host} of FRB increases with increasing redshift as should have been according to the eq. (3). This trend is caused by the cosmological evolution and is consistent with the trend obtained by [35, 36].

From Fig. 2, we notice a clear difference in the distribution of DM_{host} between repeating and non-repeating bursts. The DM_{host} comes mainly from two components: one is the contribution of the host galaxy interstellar medium, and the other is the contribution of the surrounding substance of the FRB. It should be the differences between these two components or one of them that lead to the difference in DM_{host} distribution of repeaters and non-repeaters. Generally, we can simply assume that the closer the position is to the galactic center, the larger the DM in the host galaxy of the FRB is. For this reason we first analyzed the discrepancy between the locations of repeaters and non-repeaters in host galaxies to investigate whether it is the difference in DM_{host} that causes the difference in their distribution. To make a better comparison among samples, we begin by defining the relative deviation of FRB from its host galaxy galactic center:

$$R_{offset} = \text{offset}/R \qquad (5)$$

where the offset is the projected distance of the FRB from the center of the host galaxy; R is the effective radius of the host galaxy. Later the relationship between R_{offse} and DM_{host} was analyzed. As shown in Fig. 3, DM_{host} generally exhibits a decreasing tendency with increasing R_{offse}, which is in line with our general expectation. There is no significant difference in the distribution of R_{offse} between repeaters and non-repeaters, but it can be noted that the non-repeaters near the center of the host galaxy have a larger amount of DM_{host}. This may implicate a difference in the nature of the host galaxy between repeaters and non-repeaters.

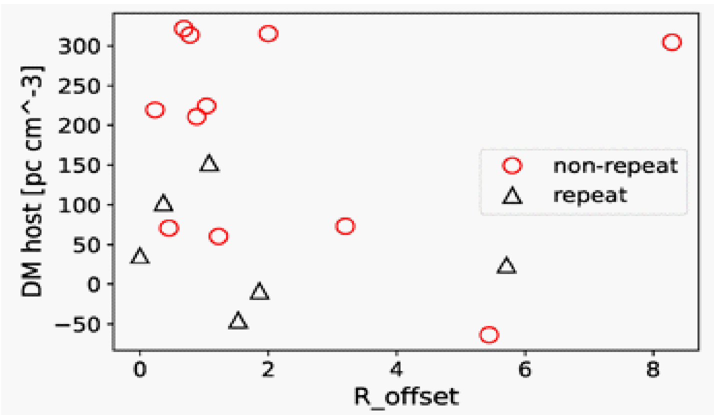

Figure 3. Relative offset value of FRB from the galactic center of the host galaxy versus the DM_{host} contribution.

We analyzed the relationship between the star-formation rate and DM_{host} contribution of repeaters and non-repeaters. As illustrated in Fig. 4, the host galaxy star-formation rate of non-repeaters has a large distribution, ranging from 0.01 - 10 $M_{\odot}yr^{-1}$, while the host galaxy star formation rate of repeaters is relatively concentrated between 0.1 - 3 $M_{\odot}yr^{-1}$.

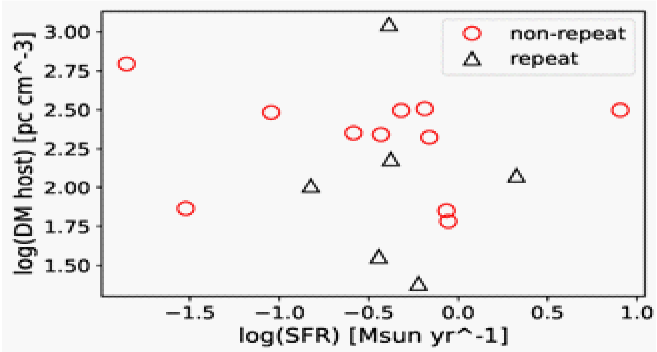

Figure 4. FRB host galaxy SFR versus DM_{host} contribution.

We further investigate whether these galaxies differ by analyzing the relationship between the mass of the host galaxy and the star formation rate. As displayed in Fig. 5, a plot of the relationship of the two variables mentioned above between repeaters and non-repeaters is shown, in which the black dashed line is an approximate boundary, described by [37, 38].

$$\log(SFR)=0.86\times\log(M)-9.29 \qquad (6)$$

The star-forming galaxies lie above this boundary. A few host galaxies lie below the boundary belong to green valley galaxies. In Fig. 5, there is no significant difference in the distribution of the host galaxies of repeaters and non-repeaters. Thus, we suggest that the variation in the DM_{host} distribution between repeaters and non-repeaters is not driven by the difference between the host galaxies, but by the difference in the localenvironment of the FRB.

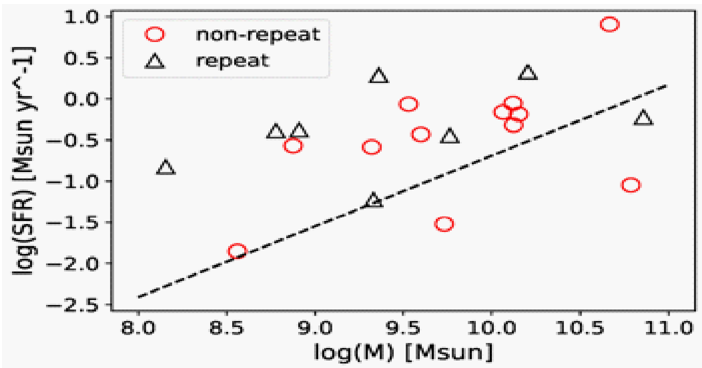

Figure 5. FRB host galaxy mass (M) versus star-formation rate (SFR). The black dashed line is the approximate boundary. Above this boundary are Star-forming galaxies and below it are Green Valley galaxies.

We have estimated DM_{host} of FRBs with known host galaxies by available physical models. The analysis finds that

(1) DM_{host} increases with redshift z, and this relation can be described by $DM_{host}=188.84\pm99.39\times(1+z)^{(0.7\pm1.96)}$;

(2) The DM_{host} distribution of repeaters has a smaller mean value and a larger distribution compared with that of non-repeaters. The mean value of DM_{host} of repeaters is $111.89^{+315.27}_{-82.58}$ pc cm^3, and that of non-repeaters is $275.81^{+107.50}_{-77.35}$ pc cm^3.

Further analysis reveals that:

(1) there is no significant difference between the distribution of repeaters and non-repeaters relative to the galactic centers, but the DM_{host} of non-repeaters near the galactic center is significantly larger;

(2) the star-formation rate of the host galaxy of non-repeaters is more widespread, ranging from 0.01 to 10 $M_{\odot}yr^{-1}$, while the star formation rate of the host galaxy of repeaters is relatively concentrated from 0.1 to 3 $M_{\odot}yr^{-1}$;

(3) there is no significant difference between the host galaxy of repeaters and non-repeaters in the distribution of log(M)-log(SFR) diagram. Most of the host galaxies belong to star-forming galaxies, and a few belong to green valley galaxies.

CONCLUSION

In summary, we suggest that there is a difference between the local environment of repeaters and non-repeaters, with more free electrons in the local environment of non-repeaters, leading to a higher DM_{host}. This finding may affect the estimation of the circumstellar magnetic field of repeaters and non-repeaters. If DM_{host} of repeaters is indeed larger than that of non-repeaters due to the influence of local matter, as we have obtained, this could to some extent restrict the physical models of the origin of repeaters and non-repeaters. For example, in this case, the origin of repeaters is less likely to be giant pulse of young pulsars since young pulsars are more likely to have a larger DM_{host} due to the association with supernova remnants.

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