

## Extragalactic dispersion measures of fast radio bursts

Jun Xu and J. L. Han

National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China;  
[xujun@nao.cas.cn](mailto:xujun@nao.cas.cn)

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**Abstract** Fast radio bursts show large dispersion measures, much larger than the Galactic dispersion measure foreground. Therefore, they evidently have an extragalactic origin. We investigate possible contributions to the dispersion measure from host galaxies. We simulate the spatial distribution of fast radio bursts and calculate the dispersion measures along the sightlines from fast radio bursts to the edge of host galaxies by using the scaled NE2001 model for thermal electron density distributions. We find that contributions to the dispersion measure of fast radio bursts from the host galaxy follow a skew Gaussian distribution. The peak and the width at half maximum of the dispersion measure distribution increase with the inclination angle of a spiral galaxy, to large values when the inclination angle is over  $70^\circ$ . The largest dispersion measure produced by an edge-on spiral galaxy can reach a few thousand  $\text{pc cm}^{-3}$ , while the dispersion measures from dwarf galaxies and elliptical galaxies have a maximum of only a few tens of  $\text{pc cm}^{-3}$ . Notice, however, that additional dispersion measures of tens to hundreds of  $\text{pc cm}^{-3}$  can be produced by high density clumps in host galaxies. Simulations that include dispersion measure contributions from the Large Magellanic Cloud and the Andromeda Galaxy are shown as examples to demonstrate how to extract the dispersion measure from the intergalactic medium.

**Key words:** galaxies: ISM — radio continuum: ISM — ISM: general

### 1 INTRODUCTION

In the Milky Way, measurements of dispersion measures (DMs) of pulsars have been used to delineate the electron density distribution of the interstellar medium (ISM). Outside our Galaxy, only 21 extragalactic pulsars in the Magellanic Clouds have DM measurements (Manchester et al. 2006). In recent years, pulsar surveys have discovered a new category of short-duration (a few milliseconds) radio bursts which are called fast radio bursts (FRBs). Due to the short duration of FRBs, the scale sizes of such exotic astrophysical events must be small. Possible origins of FRBs have been proposed, such as black hole evaporation (Keane et al. 2012), coalescence of neutron stars (Totani 2013), binary white-dwarf mergers (Kashiyama et al. 2013), supermassive rotating neutron stars collapsing to black holes (Falcke & Rezzolla 2014), synchrotron maser emission from relativistic magnetized shocks (Lyubarsky 2014), magnetar hyperflares (Popov & Postnov 2010), and nearby flaring stars (Loeb et al. 2014). Maybe some FRBs are related to gamma-ray bursts (GRBs) (e.g. Zhang 2014). To date, ten such events have been reported (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Spitler et al. 2014; Burke-Spolaor & Bannister 2014; Petroff et al. 2015; Ravi

et al. 2015). Most of these FRBs are found at high Galactic latitudes, and have large DMs up to several hundreds  $\text{pc cm}^{-3}$ , exceeding the possible Galactic foreground DM. Therefore FRBs are believed to have an extragalactic origin.

DMs of a large number of pulsars or FRBs in external galaxies can be used to detect the electron density distribution in the diffuse intergalactic medium (IGM) and ISM in the host galaxies (e.g. Dennison 2014; Zheng et al. 2014; Han et al. 2015). The DM of a given short duration source at distance ( $D$ , in units of pc) is defined as the integral of the free electron density ( $n_e$ , in units of  $\text{cm}^{-3}$ ) along the line of sight

$$\text{DM} = \int_0^D n_e dl. \quad (1)$$

The observed DM,  $\text{DM}_{\text{obs}}$ , of an extragalactic object is the sum of the DM from the host galaxy,  $\text{DM}_{\text{host}}$ , DM in intergalactic space,  $\text{DM}_{\text{IGM}}$ , and the foreground DM contributed by our Galaxy,  $\text{DM}_{\text{Gal}}$ , i.e.

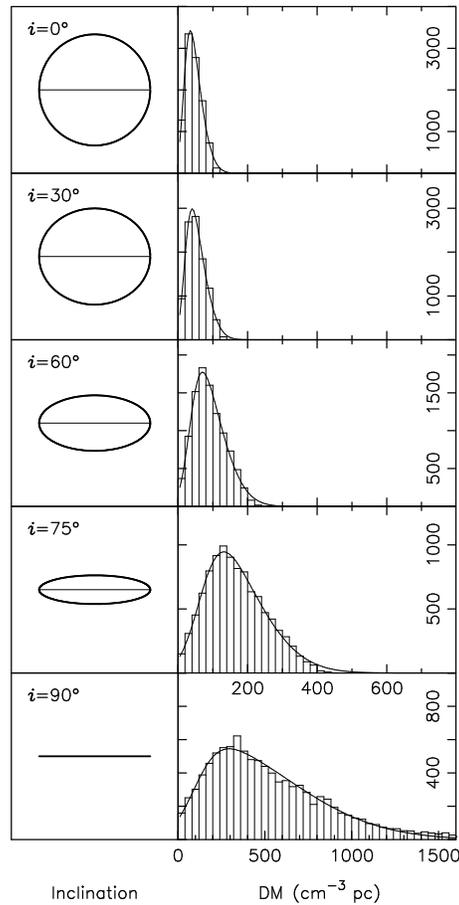
$$\text{DM}_{\text{obs}} = \text{DM}_{\text{host}} + \text{DM}_{\text{IGM}} + \text{DM}_{\text{Gal}}. \quad (2)$$

The Galactic foreground DM is the integral of electron density along the line of sight from the Sun to the furthest reaches of the Milky Way, which can be estimated by different models of free electron distribution as discussed by Schnitzeler (2012). The popular thermal electron density model for the Milky Way is NE2001 (Cordes & Lazio 2002) which is mostly built upon pulsar DM measurements. However, all known pulsars, except for 21 pulsars in the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud, are located inside the Milky Way. Therefore, the electron density distribution beyond pulsars but in the extended Galactic halo cannot be well measured at present, and hence the uncertainty of the NE2001 model in the halo region cannot be assessed. Little is known about the DMs contributed by external galaxies. Lorimer et al. (2007) estimated a probability of 25% for the DM contribution of  $100 \text{ pc cm}^{-3}$  from a host galaxy. Thornton et al. (2013) discussed the DM contribution of host galaxies and estimated  $\text{DM}_{\text{host}} \approx 100 \text{ pc cm}^{-3}$  in a spiral galaxy with a median inclination angle of  $60^\circ$ . The rough distance or redshift estimation of FRBs relies on  $\text{DM}_{\text{IGM}} = \text{DM}_{\text{obs}} - \text{DM}_{\text{Gal}} - \text{DM}_{\text{host}}$  (see Thornton et al. 2013; Lorimer et al. 2007), with the assumption of  $\text{DM}_{\text{host}} = 100 \text{ pc cm}^{-3}$ . Although the observed DMs in high-redshift galaxies can be small due to cosmological time dilation and the associated frequency shift (Zhou et al. 2014), the local DM contribution from host galaxies to FRBs is very important for calculating the DM from the IGM and then estimating their cosmological distances.

Currently, the origin of FRBs is not known, and the types and morphologies of host galaxies are also poorly constrained. In this paper, we apply Monte Carlo simulations to the spatial distribution of FRBs in a galaxy, and model the probability distribution of DM from different types of host galaxies. The NE2001 model is scaled according to the integrated  $\text{H}\alpha$  intensity to represent the electron density distributions in host galaxies. We simulate the DM contribution from spiral galaxies in Section 2, and discuss DM distributions in other types of galaxies in Section 3. In Section 4 we discuss the DM caused by clumps. In Section 5 a specific simulation for the LMC and the Andromeda Galaxy (M31) is provided. The conclusions are given in Section 6.

## 2 DM CONTRIBUTION FROM SPIRAL GALAXIES

Most FRBs probably occur in spiral galaxies with locations corresponding to stars or related objects. Here we model their spatial distribution and show their probable DM distributions. To specify the locations of any modeled FRBs, we use a Cartesian coordinate system  $(x, y, z)$  where the center of the host galaxy is at the origin. The spatial distribution of FRBs in a galaxy is described by an exponential function for height and a Gaussian radial distribution. The surface density of FRBs is therefore likely to be large near the galactic center, and decreases with radial distance. The scale height of the two-sided exponential function is set to be 330 pc, and the characteristic radius for



**Fig. 1** DM distributions of FRBs in a spiral galaxy with different inclination angles ( $0^\circ$ ,  $30^\circ$ ,  $60^\circ$ ,  $75^\circ$  and  $90^\circ$ ). The solid lines represent the fittings to the distribution with a skew Gaussian function.

the Gaussian radial density profile is set to be 6.5 kpc, similar to that for the simulation of a pulsar population (Lorimer et al. 2006).

For the Milky Way, the popular model for the density distribution of free electrons is NE2001 (Cordes & Lazio 2002). The Galactic DM along a line of sight from the boundary of the Milky Way to the Sun can be calculated through the model. For other galaxies the DMs from a host galaxy can be calculated along a sightline for the integrals of free electron density from a specific location to the near boundary of the galaxy. However, we know little about the electron density distributions in other galaxies. For a general spiral galaxy, the size and gas density structure are not very different from the Milky Way (Berkhuijsen & Fletcher 2015). We therefore model the electron density distribution in a spiral galaxy (size of  $\sim 30$  kpc) using the thin disk, thick disk, spiral arm and Galactic Center components of the NE2001 model but ignoring small-scale clumps, voids and the local ISM.

With this basic model for the electron density distribution, we use a Monte Carlo simulation to generate the spatial distribution of FRBs in a spiral galaxy for 10 000 locations. When observed FRBs come from a distant galaxy outside the Milky Way, all sightlines to these FRBs are toward us and nearly parallel. Each spiral galaxy has a specific inclination angle,  $i$ , with respect to the

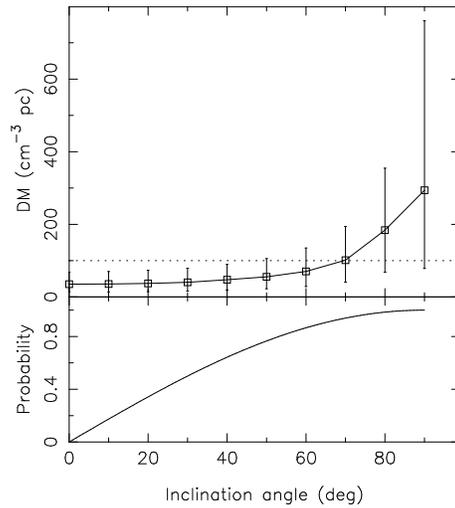
**Table 1** Fitting parameters of a skew Gaussian function for the DM distributions of FRBs in spiral galaxies for ten inclination angles, with the peak DM (column 6) and values for the left and right half width at half maximum  $W_{\text{DM-L}}$  and  $W_{\text{DM-R}}$ .

$i$ (deg)	$\xi$ (pc cm <sup>-3</sup> )	$\omega$ (pc cm <sup>-3</sup> )	$\alpha$	$W_{\text{DM-L}}$	$\text{DM}_{\text{peak}}$ (pc cm <sup>-3</sup> )	$W_{\text{DM-R}}$	$\text{DM}_{\text{median}}$ (pc cm <sup>-3</sup> )
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0	16.7	38.9	2.9	21.6	35.3	33.3	42.5
10	16.9	39.8	3.0	21.8	35.7	34.2	43.1
20	17.6	41.9	3.0	22.7	37.3	36.0	45.2
30	19.3	45.1	3.1	24.3	40.4	38.6	49.0
40	23.0	49.4	2.7	28.9	47.4	42.2	55.3
50	27.3	58.5	2.9	32.7	55.4	50.2	65.8
60	34.4	75.3	3.0	41.6	70.3	64.4	84.0
70	49.3	108.3	2.9	60.6	101.3	92.8	121.1
80	86.2	198.8	2.7	116.0	184.1	170.6	219.5
90	92.7	527.4	4.8	215.3	293.8	466.7	455.2

sightline. Obviously, FRBs behind the midplane of the disk should show a larger DM than those in front of the midplane. We calculate the DM of each FRB by integrating the free electron density in the host galaxy along the line of sight from its location to the nearer boundary at 15 kpc from the galactic center. Figure 1 shows the DM distributions for 10 000 assumed FRBs in a spiral galaxy with different inclination angles (0°, 30°, 60°, 75° and 90°). The DMs show a peak in the range of 30 to 300 pc cm<sup>-3</sup>, and shift to a large value with increasing inclination angles. The distribution follows a skew Gaussian function, defined by

$$\frac{dN}{d\text{DM}} = N_0 e^{-\frac{(\text{DM}-\xi)^2}{2\omega^2}} \int_{-\infty}^{\alpha\left(\frac{\text{DM}-\xi}{\omega}\right)} e^{-\frac{t^2}{2}} dt, \quad (3)$$

where  $\frac{dN}{d\text{DM}}$  is the number per DM, and  $N_0$  is the normalization constant;  $\xi$ ,  $\omega$  and  $\alpha$  are the location, scale and shape parameters, respectively;  $t$  is the variable used in the integral function. The results of fitting parameters for the DM distributions are listed in Table 1. The peak DM,  $\text{DM}_{\text{peak}}$ , and the left and right half width at half maximum,  $W_{\text{DM-L}}$  and  $W_{\text{DM-R}}$ , are given in columns (5) – (7) respectively. The peak DMs and the widths at half maximum are plotted in Figure 2 as a function of the inclination angle  $i$ , both of which increase very quickly at large inclination angles. The probability distribution of the inclination angles of spiral galaxies follows the function  $\sin(i)$ , as shown in the lower panel in Figure 2. The peak DM exceeds 100 pc cm<sup>-3</sup> when the inclination angle is over 70°. In a face-on galaxy, when the line of sight passes vertically through the whole disk, the DM reaches the maximum of a few tens of pc cm<sup>-3</sup>, except for the central regions that have a size of  $\sim 100$  pc where the DM can be a few hundred pc cm<sup>-3</sup> (Deneva et al. 2009). When the host galaxy is edge-on, the sightline to an FRB is at a low height and the very farthest side passes through the entire thin disk, so that the DM can be up to 4670 pc cm<sup>-3</sup>. For the peak DM and the width at half maximum, we find empirical formulae to describe  $\text{DM}_{\text{peak}} \sim 33.8 + 0.94e^{0.06i}$ ,  $W_{\text{DM-L}} \sim 22.1 + 0.21e^{0.08i}$ , and  $W_{\text{DM-R}} \sim 39.5 + 0.02e^{0.11i}$ . We calculate the ensemble distribution marginalized over the inclination angle and derive the weighted average of the DM distribution for a spiral galaxy to be 142 pc cm<sup>-3</sup>. If the FRBs follow the distribution of stars with a scale height of young Galactic Population I objects ( $\sim 100$  pc) (Gilmore & Reid 1983), the DM distribution will be more symmetric and have a narrower distribution, but the DM peaks at the same value as shown by the simulations above.



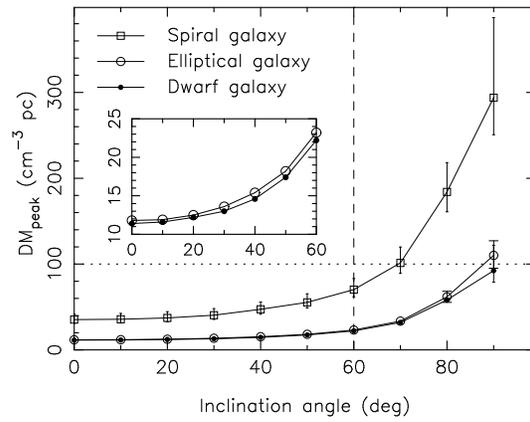
**Fig. 2** The peak DM (squares) and the width at half maximum (the vertical bars) for FRBs in spiral galaxies change with the inclination angle  $i$ . The dotted line is  $100 \text{ pc cm}^{-3}$ . The lower panel shows the probability distribution of the inclination angles oriented randomly in space, which should follow the curve  $\sin(i)$ .

### 3 DM CONTRIBUTION FROM OTHER TYPES OF GALAXIES

FRBs may also happen in dwarf galaxies or elliptical galaxies. The electron density distributions of the two types of galaxies are unknown. However, according to their shapes and structures, we can model their electron density distributions by scaling the NE2001 model according to the total intensity of  $\text{H}\alpha$  emission because  $\text{H}\alpha$  is a tracer of ionized gas. The emission measure (EM) is the pathlength integral of electron density squared, i.e.  $\text{EM} = \int n_e^2 dl$ . The total  $\text{H}\alpha$  luminosity of a galaxy is proportional to electron density squared in the volume.

Based on the galactic structures and their total  $\text{H}\alpha$  luminosity, we construct the electron density model for dwarf galaxies and elliptical galaxies, and study their DM contribution. Dwarf galaxies include irregular galaxies, dwarf spirals and dwarf ellipticals. Here, we are concentrated on young and gas-rich Magellanic type galaxies, which are typical dwarf galaxies. The size of Magellanic type dwarfs is about 1 – 5 kpc and the  $\text{H}\alpha$  luminosity is  $10^{37} - 10^{39} \text{ erg s}^{-1}$  (James et al. 2004; Kaisin et al. 2012). Magellanic type dwarfs are typical irregular galaxies, but they have un conspicuous spiral arms and disks. For simplicity, we assume that the size of a dwarf is 3 kpc and the  $\text{H}\alpha$  luminosity is  $10^{38} \text{ erg s}^{-1}$ . The total  $\text{H}\alpha$  luminosity of the Milky Way is about  $10^{40} \text{ erg s}^{-1}$ , as inferred from statistics of Milky Way-like galaxies (James et al. 2004). We scale the  $\text{H}\alpha$  luminosity of the Milky Way from a diameter of 30 kpc to the size of a dwarf (3 kpc), and set the  $\text{H}\alpha$  luminosity to  $10^{37} \text{ erg s}^{-1}$ , which is 1/10 of the observed value from a dwarf. The electron density model of a dwarf is therefore obtained by scaling the physical size to 1/10 and the amplitude to  $\sqrt{10}$  those of the NE2001 model.

Elliptical galaxies vary greatly in size, from 10 kpc to over 100 kpc. There is very little ISM in elliptical galaxies, which results in low rates of star formation. The  $\text{H}\alpha$  luminosity of a common elliptical galaxy is  $10^{38} - 10^{40} \text{ erg s}^{-1}$  (Kulkarni et al. 2014). The shapes of elliptical galaxies are similar to the bulges of spiral galaxies. Here we consider a normal elliptical galaxy with the same size as the Milky Way, and its  $\text{H}\alpha$  luminosity is  $10^{39} \text{ erg s}^{-1}$ . So, in the modeling of electron density in an elliptical galaxy, we only use the thick disk and Galactic Center components of the NE2001 model.



**Fig. 3** The peak value of DM distributions for three types of galaxies as a function of the inclination angle  $i$ . The width at half maximum is plotted in the vertical bar (scaled to 1/5 of its original value for clarity). The dotted line is plotted at the value of  $100 \text{ pc cm}^{-3}$ . The dashed line marks the half probability of the inclination angle distribution.

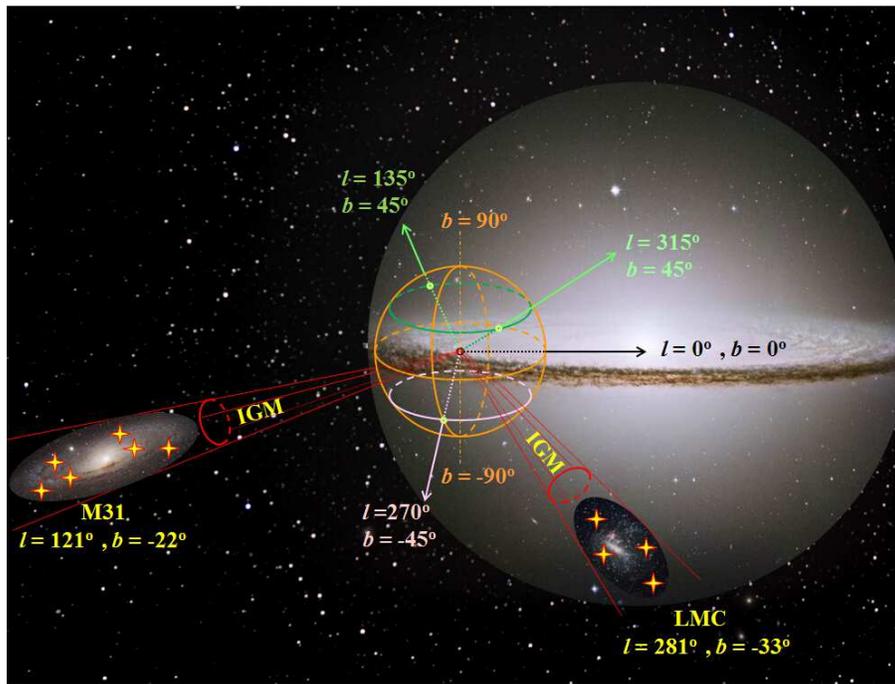
We then scale the electron density components by reducing the amplitude to  $\sqrt{1/10}$  according to the  $H\alpha$  luminosity. The inclination angle  $i$  is defined by the angle between the line of sight and normal direction of the largest plane with the major axis.

In the Monte Carlo simulations, we scale the spatial distribution of 10 000 FRBs within a galaxy accordingly. The DM distributions of FRBs in these galaxies can also be fitted with a skew Gaussian function as well, but the peak DM and the width at half maximum are much smaller than the corresponding values for spiral galaxies, as shown in Figure 3. FRBs from dwarf galaxies and elliptical galaxies have small DMs of a few to a few tens of  $\text{pc cm}^{-3}$ . The DMs increase slowly from  $11 - 12 \text{ pc cm}^{-3}$  at  $i = 0^\circ$  to  $22 - 24 \text{ pc cm}^{-3}$  at  $i = 60^\circ$ , and may reach  $100 \text{ pc cm}^{-3}$  when  $i \sim 90^\circ$ . The ensemble average of the DM distribution for a dwarf galaxy is  $45 \text{ pc cm}^{-3}$ , and for an elliptical galaxy it is  $37 \text{ pc cm}^{-3}$ .

#### 4 DM CAUSED BY HIGH DENSITY REGIONS IN A GALAXY

In the previous sections, only a large-scale diffuse ISM was considered during simulations for DM contributions from host galaxies. It is worth noting that there are thousands of small-scale high density regions in a galaxy like the Milky Way, where the electron density is strongly enhanced relative to the ambient density of the ISM. Though their volume filling factor is quite small (with the maximum of a few tens of pc), the sightline toward an FRB to pass through a clump would produce significant DM.

Clumps of ionized gas most likely correspond to discrete H II regions. To date, more than 2500 H II regions have been observed in our Galaxy (Hou & Han 2014). Their distribution is very inhomogeneous and most of them are concentrated in spiral arms. Extragalactic H II regions are also found in spiral galaxies and irregular galaxies, but very few are detected in elliptical galaxies (Zhou et al. 2014). The size of a Galactic H II region ranges from a few percent of a pc (ultracompact) to several tens of pc, which is roughly inversely proportional to the electron density in an H II region. The typical size and average electron density of H II regions detected by the Sino-German 6 cm Polarization Survey (e.g. Sun et al. 2007; Gao et al. 2010; Sun et al. 2011; Xiao et al. 2011) are a few tens of pc and a few  $\text{cm}^{-3}$ , respectively. The DMs caused by the clumps range from tens of  $\text{pc cm}^{-3}$  to hundreds of  $\text{pc cm}^{-3}$  according to previous studies of pulsars in our Galaxy. Therefore, if an FRB in



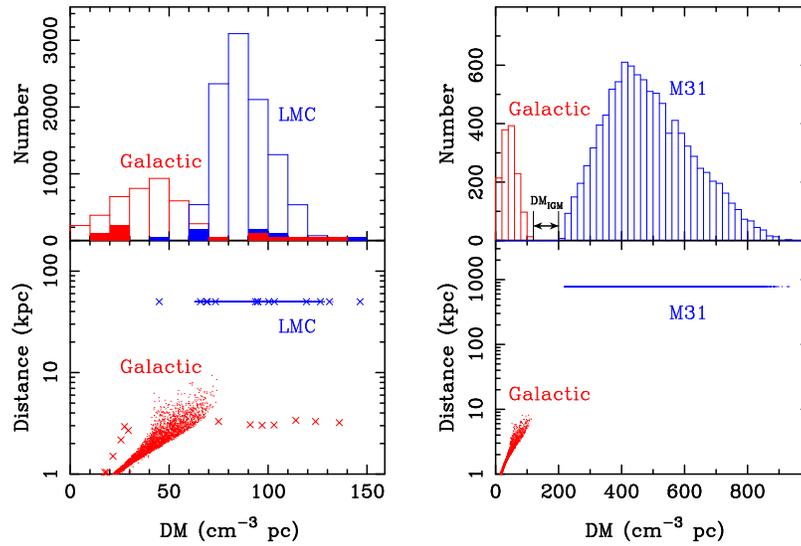
**Fig. 4** A schematic diagram showing the locations of the LMC and M31 in Galactic coordinates.

the host galaxy happens to take place behind a clump, a large part of the observed DM could come from the clump.

## 5 APPLICATIONS IN THE LMC AND M31

In the near future, a next generation radio telescope, the Square Kilometre Array (SKA), will reveal the electron density distribution in nearby galaxies and the IGM (Han et al. 2015). DM measurements of extragalactic pulsars and single pulses are the first powerful probes that can be used to detect the extragalactic medium, including ISM in a host galaxy and IGM. A large sample of pulsars or FRBs in nearby galaxies such as the LMC and M31 will be detected by this highly-sensitive telescope (see Keane et al. 2015). A large sample of Galactic pulsars in the region of sky immediately around the direction of the host galaxy can be used to estimate the foreground column density of electrons in the Milky Way. After discounting the foreground DM contribution from our Milky Way and constraining the local contribution from the host galaxy, the DM from IGM can be derived from observations of extragalactic pulses. Here, we apply the simulations for host galaxies of the LMC and M31, to demonstrate the detection of intergalactic DM.

The LMC is a satellite of our Milky Way, at a distance of about 50 kpc (Pietrzyński et al. 2013) in the southern hemisphere of the sky ( $l = 280.5^\circ$ ,  $b = -32.9^\circ$ ). Its size is about 4.3 kpc, with an inclination of  $\sim 35^\circ$  (e.g. Nikolaev et al. 2004). At present, 15 pulsars have been discovered in the LMC, and their DMs have been estimated for 13 pulsars (Manchester et al. 2006). M31 is the largest galaxy in the Local Group, with a distance of approximately 780 kpc (Staneke & Garnavich 1998) in the direction ( $l = 121.2^\circ$ ,  $b = -21.6^\circ$ ). M31 is estimated to have an inclination angle of  $77^\circ$  (e.g. Chemin et al. 2009). The apparent diameter is about 40 kpc. Their locations relative to the Milky Way are illustrated in Figure 4. The simulations mentioned in Sections 2 and 3 are scaled for the



**Fig. 5** Simulated DM distributions of extragalactic pulsars (blue) and Galactic pulsars (red) within a  $10^\circ$  radius around the LMC *on the left* and M31 *on the right*. A small sample of pulsars in the LMC and a small sample of foreground Galactic pulsars around the cloud are marked with crosses (*lower left panel*) and presented with as the *scaled* filled area of the histogram (*upper left panel*). Currently the NE2001 model of electron density distribution is not good enough for reconstructing the DMs of foreground pulsar data. However, in the future, SKA will discover a much larger sample of Galactic pulsars to improve the electron density distribution model and discover many extragalactic pulsars (e.g. in M31) that can be used to deduce the DM contribution from host galaxies and the IGM.

LMC and M31, respectively, as shown in Figure 5. We simulate foreground Galactic pulsars within a  $10^\circ$  radius around the directions of host galaxies. The “observed” DMs from the host galaxies in Figure 5 are the sum of DM from the host galaxies, DM in the IGM and the foreground DM contributed by our Galaxy in their directions. We add  $DM_{\text{IGM}}$  of  $10 \text{ pc cm}^{-3}$  for the LMC, and  $150 \text{ pc cm}^{-3}$  for M31 according to their distance.

Current data for pulsars in the LMC and in the Milky Way near the direction of LMC are compared with a simulated pulse distribution in the left panel of Figure 5. Obviously, the current NE2001 model of electron density distribution is not good enough to reconstruct the DMs of farthest Galactic pulsars. It is expected that an improved electron density distribution model can be constructed in the future. The simulated DMs for pulsars in the LMC are very consistent with the observed DMs of LMC pulsars, except for two outliers.

As pointed out by Han et al. (2015), it is difficult to estimate the dispersion contributed by the host galaxy for only an individual extragalactic pulsar or pulse. A large sample of pulsars is required for this purpose. As shown in the right panel of Figure 5, the minimum DM of these pulsars,  $\min(DM_{\text{extraPSRs}})$ , can be expressed as the upper limit of  $DM_{\text{IGM}}$  plus the foreground Galactic DM,  $\max(DM_{\text{GalacPSRs}})$ . The electron density of the IGM can be estimated by  $DM_{\text{IGM}} = \min(DM_{\text{extraPSRs}}) - \max(DM_{\text{GalacPSRs}})$ . When large samples of pulsars or FRBs in a host galaxy and also in the Galactic region in the general direction of a host galaxy are discovered by SKA in the future, the electron density distribution model for the Milky Way will be greatly improved, and the DM contribution from the host galaxy and the IGM can then be deduced.

## 6 CONCLUSIONS

We apply Monte Carlo simulations to generate the spatial distribution of FRBs in a host galaxy. The electron density distribution of the host galaxy is modeled by using the scaled model of NE2001. The DM distributions of FRBs from the host galaxies are calculated for different types of galaxies, which roughly follow a skew Gaussian function. The characteristic parameters of the skew Gaussian function increase with inclination angle. FRBs or pulsars in spiral galaxies can have a large DM when the inclination angle of the galaxy is over  $70^\circ$  and the sightline of an FRB passes through the central region. The largest DM can reach a few thousand  $\text{pc cm}^{-3}$  when a galaxy is edge-on. The possible DM distributions of pulsars or FRBs in dwarf galaxies and elliptical galaxies are in the range of a few to a few tens of  $\text{pc cm}^{-3}$ . In addition, high density clumps will induce a large DM for pulsars or FRBs of tens to hundreds of  $\text{pc cm}^{-3}$  if they are behind the clumps.

In the future when many FRBs or extragalactic pulsars are detected, the statistics of their DM distribution can be used to derive the DM contribution by the host galaxy and derive the intergalactic DMs after discounting the foreground Galactic DMs.

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