The Host Galaxy of a Low Dispersion Measure Fast Radio Burst

Marcus Merryfield

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1 Scientific Justification

1.1 Astrophysical Significance

Fast Radio Bursts (FRBs) are bright (∼Jy), short (∼ms) radio transients first discovered in 2007 by Lorimer et al. (2007) (see Katz, 2016, for a brief review). The origins of FRBs are unknown, and an abundance of theories exist to explain them. For example, one popular theory ties FRBs to synchrotron maser emission from magnetar flares (Lyubarsky, 2014), with the single known repeating source FRB 121102 being potentially explained by the birth of a millisecond magnetar (Metzger et al., 2017). However, theories as extreme as alien light sails (Lingam & Loeb, 2017) have been published to try and describe these mysterious transients. Whether all FRBs repeat or whether there are two populations (repeating and cataclysmic FRBs) is still unknown.

FRBs are dispersed by the tenuous plasma that exists along the line of sight, leading to a smearing of the signal over time with a frequency dependence of $\delta t \propto \nu^{-2}$. This smearing is characterised by the dispersion measure (DM) of the FRB, defined as the integrated electron density along the line of sight. The milky way (MW), the FRB host galaxy, and the intergalactic medium (IGM) all add a contribution to the observed DM ($\mathrm{DM_{obs}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{Host}}$). The DM of FRBs has been shown to be in considerable excess of the milky way contribution based on models from galactic pulsar DMs by Cordes & Lazio (2002) and Yao et al. (2017), implying an extragalactic origin for FRBs. The DM contribution from the IGM is also readily estimated (Zheng et al., 2014), leaving the most ambiguous DM contribution to be that of the host galaxy.

The ability to link events to host galaxies will be an extreme advancement in our understanding of FRBs. Currently, only ‘the repeater’ (FRB 121102) has been unambiguously localised to a host galaxy (Tendulkar et al., 2017). The repeater’s host galaxy is at a redshift $z = 0.193$, corresponding to a luminosity distance $D_{\mathrm{L}} = 972$ Mpc assuming cosmological parameters from the Planck Collaboration (Planck Collaboration et al., 2016). Based on the spectral properties and absolute magnitude from Gemini observations, Tendulkar et al. (2017) classify the repeater’s host galaxy as a low-metallicity, star-forming dwarf galaxy. This characterisation, as well as the estimated DM contribution from the host, have helped constrain models of FRB 121102.

Understanding the environments of FRBs is of critical importance. For example, one potential use of FRBs is as a probe of the baryonic matter in the IGM (Zheng et al., 2014), as the DM of FRBs gives an accurate measure of the electron density (which can be linked to baryon density) along the line of sight. This may resolve the so called ‘missing baryon problem’: adding up the mass contribution of baryons seen in current observations can only account for about half of the baryon content predicted by the cosmic

	Width (ms)	DM (pc cm^{-3})	R.A. (deg.)	Dec. (deg.)	SNR	$\tau_{600\ \mathrm{MHz}}$ (ms)
FRB XXXXXX	0.31±0.08	212.8±0.5	103.28±0.12	36.82±0.07	34.5	1.1±0.13

Table 1: The properties of FRB XXXXXX, fit using a simple frequency-independent Gaussian burst profile. The values correspond to the median of MCMC samples with uncertainties given as 1σ. The equivalent width of the burst, its dispersion measure, R.A., Dec., SNR, and scattering time at 600 MHz ($\tau_{600\ \mathrm{MHz}}$ are given. The fit of beam 0 (see Figure 2) was used, as it had the highest SNR.

Model	NE2001	YMW16
DM_{obs}	212.8	212.8
DM_{MW}	94.6	122.9
DM_{halo}	30.0	30.0
DM_{IGM}	88.2	59.9
z	0.097	0.065

Table 2: Estimates for DM contributions (in pc cm^{-3}) for FRB XXXXXX from the MW, MW halo, and IGM, assuming no host contribution. Corresponding redshift estimates based on DM_{IGM} are given, calculated from Equation 8 of Zheng et al. (2014) assuming the results of Planck Collaboration et al. (2016). Two MW electron density models were used (NE2001 and YMW16, Cordes & Lazio, 2002; Yao et al., 2017, respectively).

microwave background (CMB) (Bregman, 2007). Unless the DM contribution of the FRB host galaxy is well understood, however, there is a significant uncertainty when using FRBs as probes of baryonic matter.

Galaxy associations also allow the redshift of FRB sources to be determined. Besides redshifts crucially revealing a distance scale (and thus an energetic scale, given a flux) for FRBs, there are other important consequences as well. By exploring the distribution of DM as a function of redshift, the epoch of helium II (He II) reionization around $z \approx 3$ may be explored. Since helium accounts for a non-negligible percentage of the electron density in the IGM, it is expected that the DM of FRBs around He II reionization will increase. A characterisation of how the electron density changes during this epoch holds importance in understanding how quickly these kinds of phase transitions occur in the universe. Figure 1 shows an example of what a theoretical DM-redshift relation from FRBs might look like.

While the localisation of the repeater is certainly interesting, one data point is not enough to understand the properties of FRB host galaxies. In order to further understand FRBs, it is a necessity to associate them with their hosts in order obtain redshifts and host DM contribution estimates. This will develop the understanding of FRB energetics to help constrain source models, as well as more precisely reveal the electron density in the IGM across multiple epochs.

1.2 The CHIME Telescope

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a new radio telescope which has recently begun its pre-commissioning phase. The CHIME/FRB experiment samples CHIME's 250 square degree feield of view at 1 ms cadence, and hopes to find FRBs at rates of 2$\sim$50 FRBs day^{-1} once it has finished its commissioning phase (CHIME/FRB Collaboration et al., 2018). CHIME/FRB has already begun detecting FRBs in realtime (Boyle & Chime/Frb Collaboration, 2018). While the first detected CHIME/FRB had a DM of 716.6 pc cm^{-3} which would imply its origin at $\sim$cosmological distances, there exist events detected with other instruments that have much lower DM and may originate in the more local universe (see the FRB catalogue[1], Petroff et al., 2016).

CHIME/FRB has recently detected a new low DM (212.8 pc cm^{-3}) event, FRB XXXXXX (see Table 1). Based on DM estimations of the MW from two models (Cordes & Lazio, 2002; Yao et al., 2017), as well as an assumed constant MW halo value of $DM_{\mathrm{halo}} = 30.0$ pc cm^{-3} (see Dolag et al., 2015), we computed the contribution of the IGM to the observed DM, and converted it to a redshift using Equation 8 from Zheng et al. (2014) (see Table 2). As no host contribution was assumed, this gives an upper redshift limit of $z \sim 0.1$ for the host galaxy of FRB XXXXXX. We searched the NASA Extragalactic Database[2] and found no catalogued galaxies with known redshift in the localisation error region of FRB XXXXXX.

We request 4500s of Gemini North Multi-Object Spectrogroph (GMOS-N) imaging time. Our goals with these observations are as follows:

- Resolve candidate host galaxies of FRB XXXXXX in a five square arcminute field of view around the source.

[1] `http://frbcat.org/`
[2] `https://ned.ipac.caltech.edu`

- Determine a photometric redshift for the galaxies in the field of view, and rule out those further than the redshift limit in Table 2.
- Classify candidate galaxies through fitting their morphology and determining their absolute magnitudes.
- Select the best candidates for follow-up spectroscopy.

2 Technical Justification

We propose the followup of FRB XXXXXX with 4500s of observations using the GMOS-N instrument. First, three imaging observations will be centred on the (R.A., Dec.) coordinate pair given in Table 1. Each observation will be taken with one of the Gemini g', r', and i' filters respectively. Using the GMOS-N Integration Time Calculator (ITC[3]), we calculated the time necessary to achieve a minimum SNR of 5σ in 900s observing windows for each of the filters. The fiducial target for these calculations was a Gaussian profile with a FWHM of one arcsecond, a spatially integrated brightness of $m_{r'} = 25.0$ AB mag, and the spectrum of a Sc type spiral galaxy mapped to $z = 0.1$. These parameters were chosen to broadly mimic the host galaxy of FRB 121102 (Tendulkar et al., 2017). Observing conditions were chosen to be of the 70th percentile for image quality (see Gemini's image quality table[4]), with patchy/thin cloud cover, any level of water vapour, and a V-band sky brightness greater than 20.7 mag/sq arcscec (50th percentile). Table 3 gives a summary of requested time based on results from the GMOS-N ITC.

Filter	g'	r'	i'
Integration Time	1800s	1800s	900s
Number of Observations	2	2	1
Resulting SNR	5.94	7.05	6.53

Table 3: Summary of observations using results from the GMOS-N ITC. Three observations will be made with each of the g', r', and i' filters, for a total of 4500s of exposure across 5 observations.

[3] http://www.gemini.edu/sciops/instruments/integration-time-calculators/gmosn-itc
[4] https://www.gemini.edu/sciops/telescopes-and-sites/observing-condition-constraints#ImageQuality

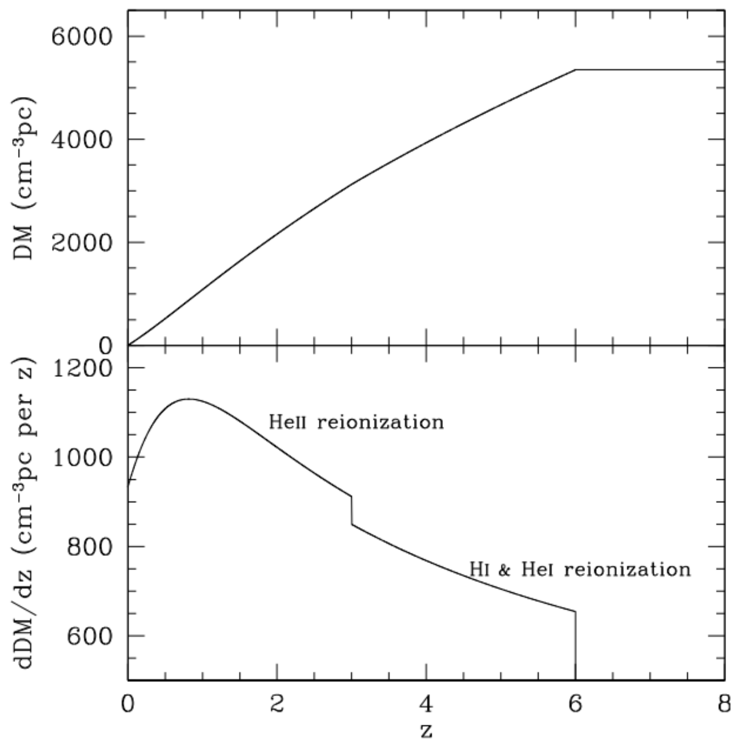

Figure 1: An illustration of how dispersion measure might be used to probe the epoch of reionization of He II. DM and DM derivative as a function of redshift are shown, with an assumed instantaneous rise in DM at H I/He I reionization ($z \sim 6$) and He II reionization ($z \sim 3$).

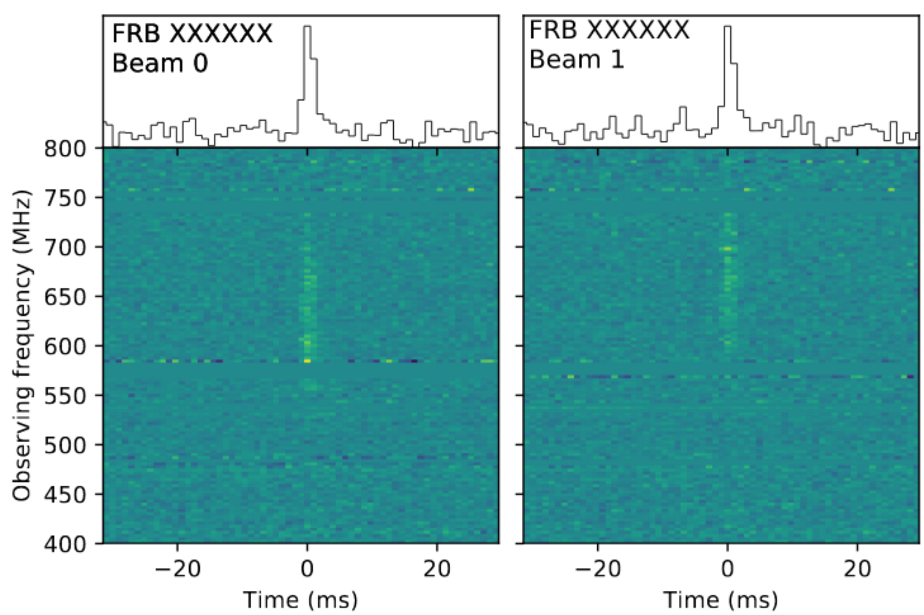

Figure 2: A dynamic spectrum of FRB XXXXXX. The event was detected in two adjacent North-South beams, with Beam 0 having the larger detected SNR. Time is relative to the topocentric arrival time of the burst at 400 MHz. Some channels with terrestrial radio frequency interference (RFI) are zero-weighted.

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