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Uncovering the Origins of Fast Radio Bursts Using Local Universe CHIME Discoveries

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Abstract

Fast radio bursts (FRBs) are one of astronomy's greatest mysteries. These millisecond-duration radio pulses are powerful enough to be observed from distant galaxies and can probe the distribution of ionized baryons throughout the Cosmic Web. However, their origins remain a mystery owing primarily to the small sample of localized FRBs. The Canadian Hydrogen Mapping Experiment (CHIME) telescope, a transit radio interferometric array in Canada, has produced the largest FRB catalog to date. For a fraction of the cataloged bursts, we saved raw voltage data that facilitated their sky localization to sub-arcminute precision. This precision is sufficient to identify the host galaxies of local Universe CHIME FRBs (redshift z $<$ 0.1). In this summary paper, we report on the identification of several nearby FRBs which include the two closest FRBs known to date, FRBs 20200120E and 20181030A. These local Universe bursts have constrained FRB emission mechanisms and progenitor models and have disfavoured many previously held assumptions about the population of FRBs. Finally, we use the local Universe FRBs with known hosts and derive a mean MW halo DM estimate of 32^{+16}_{-20} pc cm^{-3} (95% confidence limit) from a joint Bayesian analysis.

1 Introduction

Fast radio bursts (FRBs) are energetic radio pulses of high brightness temperature ($\sim 10^{35}$ K) and millisecond duration [1]. In spite of the fact that more than 1000 FRBs have been discovered to date[1], their nature continues to be a subject of intense debate, owing in part to a limited sample of localized FRBs. To unveil the nature of FRB sources, identification of FRB multi-wavelength counterparts as well as detailed analyses of their hosts and local environments are promising approaches. However, due to the limited sensitivity of current telescopes, these approaches are best suited for local Universe FRBs [3].

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a transit radio telescope operating in the frequency range of 400-800 MHz [4] (see Figure 1). Due to its enormous instantaneous field-of-view ($\sim$ 220 sq.deg.), large collecting area (8000 sq.m.), broad frequency coverage (400-800 MHz), and highly sophisticated software backend, CHIME has revolutionized the FRB field by discovering the majority of all known FRB sources to date [5]. For some of the CHIME FRBs, we acquire raw voltage data that can facilitate localization to sub-arcminute or a few arcminutes precision [6] using a novel technique of fast Fourier transform beam-forming [7]. This angular resolution is sufficient to identify host galaxies of local Universe FRBs due to the low number density of nearby galaxies [3]. In Section 2, we describe four recently published local Universe CHIME FRBs [3, 8, 9] and the major implications of these discoveries. Finally, we conclude in Section 3.

[1]For a complete list of known FRBs, see the TNS [2].

Figure 1. Photograph of the CHIME telescope located at the Dominion Radio Astrophysical Observatory (DRAO) in British Columbia, Canada.

2 Sample of low-DM CHIME FRBs

In order to select local Universe CHIME FRBs, we only consider bursts with saved baseband data and whose dispersion measure excess (DMex), a measure of the total free electrons outside the Milky Way disk that the FRB pulse interacted with, is $<$ 100 pc cm^{-3}. The DMex $\leq$ 100 pc cm^{-3} assured that the FRB source is located within the luminosity distance of $\sim$ 500 Mpc (or redshift z $<$ 0.1), using the Macquart relation [10]. We found ten FRBs in the first CHIME/FRB catalog that satisfies this criterion. Here we discuss four of them; the host galaxies of the remaining six FRBs will be reported in a publication soon (Bhardwaj et al., in prep). Two of the four local Universe FRBs [3, 8], FRBs 20181030A and 20200120E, are the closest known extragalactic FRBs to date, and for one FRB, FRB 201903030A [9], we found a merging pair of star-forming galaxies as its most promising host. For all but one FRB, FRB 20180814A, we were not able to make a firm association (chance association probability < 1%). Therefore, we reported a tentative host of FRB 20180814A in [9]. The host galaxy of three FRBs with robust host associations are shown in Figure 2. Now, we summarize the major implications of these local FRB discoveries.

2.1 Multiple FRB formation channels

On April 28, 2020, CHIME [11] and STARE2 [12] detected an FRB-like event in conjunction with a hard X-ray burst from a Galactic magnetar SGR 1935+2154. This discovery established magnetars as a most promising source of FRBs. However, we discovered the repeating fast radio burst source FRB 20200120E discovered with CHIME/FRB [3], the closest extragalactic FRB discovered to date, located in a nearby grand-design spiral galaxy, M81, at a distance of $\sim$ 3.6 Mpc. From the subsequent follow-up campaign, this FRB source was found to be located in an M81 globular cluster [13], which we had identified as one of the possible counterparts in our discovery paper [3] (see Figure 1). This is perplexing because the most popular FRB model invokes young magnetars as sources, which are produced via core-collapse supernovae. However, because globular clusters harbor extremely old stellar populations, that model cannot explain the source of FRB 20200120E. Therefore, this discovery provides the strongest evidence yet of the existence of multiple FRB populations.

2.2 FRBs localized to diverse galaxies

Till 2021, most of the localized FRBs are either located in either star-forming or green-valley galaxies [14]. Moreover, localized repeating FRBs are found in galaxies with lower stellar masses and higher star formation rates than non-repeating FRBs. However, the host galaxies of repeating FRBs 20180814A and 20190303A challenged this observation [9]. For FRB 20180814A, the promising host we found is PanSTARRS-DR1 J042256.01+733940.7, a nearby (z= 0.06835) passive red spiral galaxy, and for FRB 20190303A, we associate the source to a local Universe merging pair of two star-forming galaxies at a redshift of 0.064, SDSS J135159.17+480729.0 and SDSS J135159.87+480714.2. These associations clearly show that the repeating FRB sources are located in diverse environments, and argue that more FRB host localizations are required to uncover the global properties of the FRB host population.

2.3 Are all FRBs repeating sources?

We can use our sample of local Universe FRBs with known hosts ($<$ 150 Mpc), that were discovered between 2018 July 25 and 2019 and July 2 and were published in the first CHIME/FRB catalog, to estimate a lower limit of the FRB volumetric rate. Using the total exposure time of the CHIME telescope during the aforementioned duration [5], we estimated a lower limit on the volumetric rate of FRBs ($\leq 10^{38}$ erg s^{-1}) to be $\sim 2.5 \times 10^7$ Gpc^{-3} yr^{-1}. The estimated FRB volumetric rate is at least 100 times higher than the observed volumetric rate of core-collapse supernovae in the local Universe [15]. If the core-collapse supernovae are the most common way to produce compact objects $-$ proposed sources to produce FRBs $-$ FRBs detected at low luminosities ($\leq 10^{38}$ erg s^{-1}) are therefore more likely to be repeating sources.

2.4 Measuring ionized baryons in the Milky Way circumgalactic medium

Our sample of local Universe FRBs with low excess DM provides the most constraining limit on the Milky way halo DM along their respective sightlines. Additionally, we employed a Bayesian framework (Bhardwaj et al., submitted) and combined the constraints from the five local Universe FRBs with known hosts and with excess DM $<$ 100 pc cm^{-3}, to derive a mean MW halo DM estimate of 32^{+16}_{-20} pc cm^{-3} (95% confidence limit). This limit rejects models (see for more discussion on this) that predict Milky Way halo DM $>$ 50 pc cm^{-3} (for example, PZ19 model [16]).

3 Conclusion

In this summary paper, we report on the discovery and host association of several low excess-DM CHIME FRBs, two of which, FRBs 20181030A and 20200120E, are the closest known extragalactic FRBs to date. These local Universe FRBs described have constrained FRB emission mechanisms and progenitor models and disfavoured a number of previously held beliefs regarding the FRB population. For instance, the hosts of the four repeating FRBs have strikingly distinct physical properties, which raises questions about the kinds of conditions that could produce FRBs in galaxies with significantly different properties. Furthermore, FRB 20200120E was later localized to the M81 globular cluster by [13] that we reported in our work. The most popular FRB model evokes young strongly magnetized and compact objects. It is highly unlikely that the FRB 20200120E source was formed through this channel. Therefore, the association provides the strongest evidence yet for the existence of multiple FRB formation channels. We also used our sample of local Universe FRBs to constrain the mean contribution of the Milky Way halo dispersion measure which is currently of the most constraining empirically derived limit.

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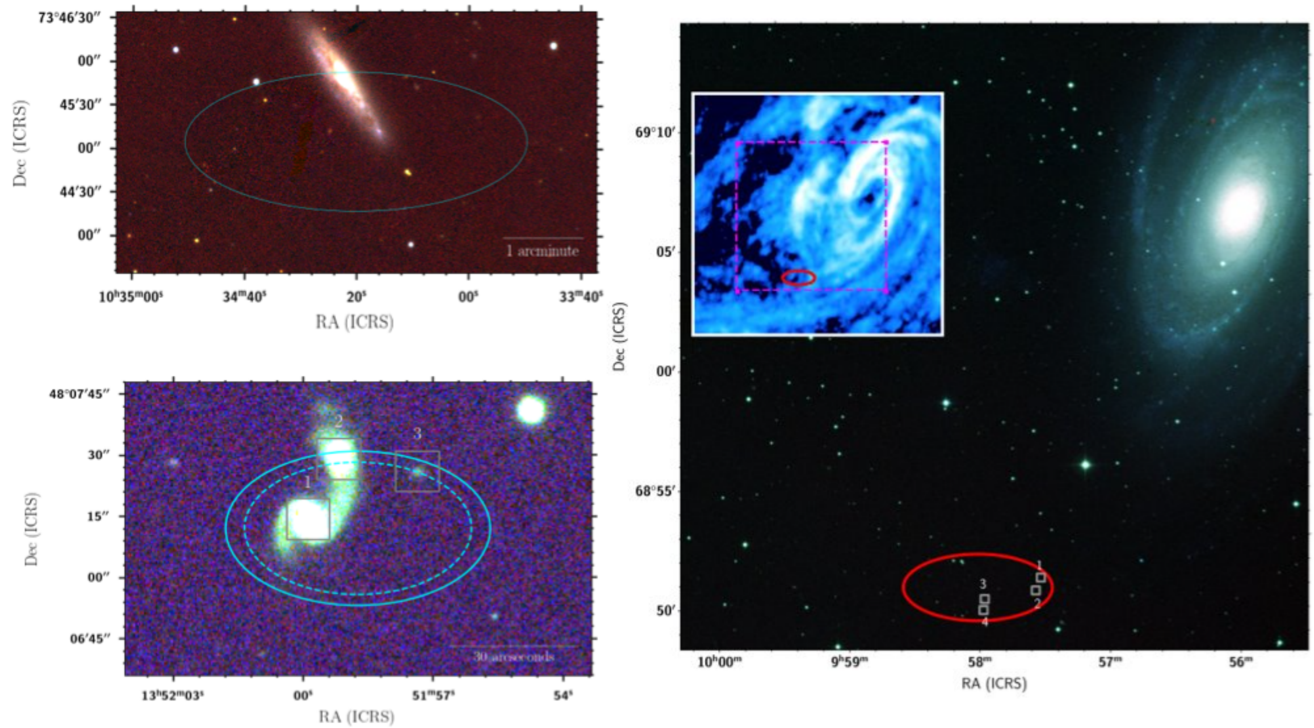

Figure 2. Low-DM CHIME FRBs: The figure shows a subset of localized low-DM CHIME FRBs: (top left) FRB 20181030A host (NGC 3252; 20 Mpc), (bottom left) FRB 20190303A host (Merging pair, [PA2008] 207.996573+48.12472; z = 0.064), and (right) FRB 20200120E host (M81; 3. Mpc). In each plot, a solid ellipse represents a 90% confidence localization region.

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