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FAST RADIO BURSTS WITH CHIME

C. Ng[1] and the CHIME/FRB Collaboration

Abstract. A few days before SF2A 2021, the CHIME radio telescope released its first catalog which consists of over 500 FRB discoveries. In this article, we will review the CHIME/FRB project and discuss some of its highlight discoveries reported so far. We will end with a brief on-look at the next generation radio telescope facilities, which aim to improve localization capability of FRB surveys.

Keywords: Fast Radio Bursts, radio transient, radio telescope

1 Introduction

Since the first report of an extragalactic Fast Radio Burst (FRB) detection in 2007 (Lorimer et al. 2007), the origins of these bright, short-duration bursts of radio waves have been a highly contentious topic. Our knowledge of FRBs has been limited since only a few tens of cataclysmic FRBs were observed in this first decade. The FRB field has been revolutionized in the last few years, much of this is thanks to the hundreds of FRBs discovered by CHIME, the Canadian Hydrogen Intensity Mapping Experiment.

2 The CHIME/FRB system and its highlight discoveries

CHIME is a radio telescope located at the Dominion Radio Astrophysical Observatory (DRAO) in Penticton, British Columbia in Canada. CHIME has been built by students and researchers on the team. The construction took over three years and was completed in late 2017. It consists of four half-pipe like cylinders placed side by side, spanning an area of $100\,\mathrm{m}\times 80\,\mathrm{m}$. On each of the four focal lines is a linear array of 256 dual polarization clover-leaf antennas. This telescope design provides a much larger field-of-view (FOV) compared to a single dish radio telescope of comparable sensitivity. This is one of the reasons why CHIME has been such a game changer in the study FRBs: with the over 200-squared-degree FOV, CHIME has a proportionally higher chance in detecting FRBs bursting in *a priori* unknown location and time.

An overview of the CHIME data acquisition and real-time analysis pipeline can be found in CHIME/FRB Collaboration et al. (2018). To summarize, a Fast Fourier Transform (FFT)-based beamforming algorithm enables 1024 coherently pointed beams to be formed simultaneously to tile CHIME's FOV (Ng et al. 2017; Masui et al. 2019). We up-channelize the data to improve frequency resolution of our data to 24 kHz sampled at 0.983 ms to minimize the effect of intra-channel smearing. This intensity data output is searched for FRB signals using a tree-style dedipsersion algorithm called BONSAI, which covers a large parameters space up to a maximum dispersion measure (DM) of $13{,}000\,\mathrm{pc\,cm^{-3}}$. A ring buffer constantly stores a short window (up to 240 s) of the most recent baseband data, which allows us to trigger a baseband dump when a high signal-to-noise FRB candidate is detected. The localization of the bursts can then be refined during a subsequent offline analysis, as well as enable the extraction of any polarization information (Michilli et al. 2021). Below are some of the highlight discoveries CHIME has reported to-date.

2.1 A large population of FRBs

Within the first two months of operation, 13 new FRBs were reported by CHIME, providing proof that FRBs do exist at the relatively low frequency range of 400−800 MHz (CHIME/FRB Collaboration et al. 2019b). Between July 2018 and July 2019, CHIME has detected 536 FRBs (see Fig. 1), which formed the basis of its first Catalog release (CHIME/FRB Collaboration et al. 2021a).

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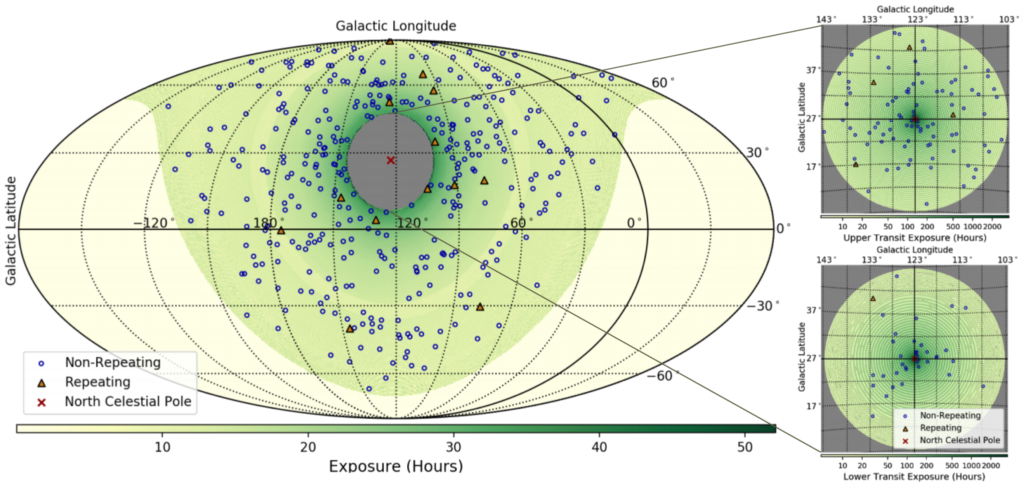

Fig. 1. The 536 FRBs reported in the CHIME Catalog 1. The colour scale represents the non-uniform exposure of CHIME as a function of sky position. The region around the North Celestial pole requires special treatment, since it is visible at CHIME twice a day at the upper (**top right panel**) and lower (**bottom right panel**) transients where the telescope sensitivity are very different. Figure adapted from CHIME/FRB Collaboration et al. (2021a).

From this FRB sample, we conclude that the FRB luminosity function is consistent with a power-law index of $\alpha = -1.40 \pm 0.11$, which is what is expected from an Euclidean sky distribution. The overall sky rate is 818 ± 64 /sky/day, considering FRBs with fluence ≥ 5 Jy ms, at DM $\geq 100\,\mathrm{pc\,cm^{-3}}$ and with scattering time $\tau_{600} \leq 10$ ms. There is no evidence for Galactic latitude dependence of the FRB sky distribution (Josephy et al. 2021), contrary to what was suggested in some of the earliest FRB literature. Furthermore, we detect significant correlation between the Catalog 1 FRBs and large scale structure of the Universe (Rafiei-Ravandi et al. 2021). We obtain a p-value of $\sim 10^{-4}$ after accounting for look-elsewhere effects in redshift and angular scale. This is observed to be true over a wide range of redshifts between $0.3 \leq z \leq 0.5$.

2.2 Repeating FRBs

The CHIME Catalog 1 also confirmed the existence of multiple FRB populations, notably one that consists of one-off, cataclysmic bursts and one that consists of repeating FRBs. We have compared the morphology of the one-off and the repeating FRBs. From Pleunis et al. (2021a), it is apparent that repeating FRBs have wider pulses and narrower emission bandwidths compared to the non-repeating population. We also note that no obvious differences are present in other parameters such as DM, scattering time, and the flux density. In order to facilitate quick follow-up observations by other telescope facilities, CHIME is now releasing any new and latest repeating bursts on a public server*.

Repeating FRBs are particularly interesting because it is easier to obtain more information of these bursts through re-observations. CHIME has thus far published 18 repeaters (CHIME/FRB Collaboration et al. 2019a,c; Fonseca et al. 2020). Fig. 2 gives a visual representation of the bursts occurrence of these 18 sources. Already by eye we can tell that they repeat on a range of cadence, although there is some level of clustering. Upon a more in-depth analysis, we find that one of the repeaters, FRB 20180916B (nicknamed R3 within the collaboration and in Fig. 2) has a 16.35-d periodic activity cycle (The CHIME/FRB Collaboration et al. 2021). The activity window lasts for roughly 4-d each time. One LOFAR team conducted simultaneously observations with CHIME and the upgraded Giant Metre Wavelength Radio Telescope (uGMRT). They have shown that the burst activity is systematically delayed toward lower frequencies by about 3 d from 600 to 150 MHz (Pleunis et al. 2021b). Furthermore, one other repeater FRB 20191221A shows sub-second periodicity among its multi-component profile (CHIME/FRB Collaboration et al. 2021b).

*https://www.chime-frb.ca/repeaters

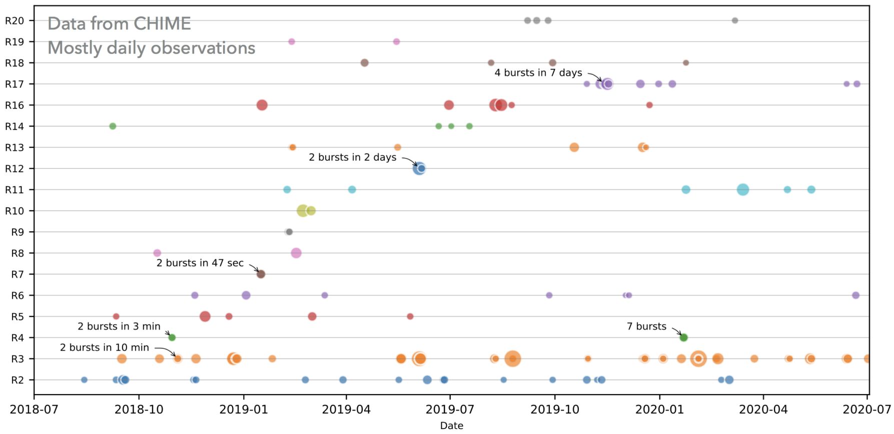

Fig. 2. The burst occurrence of the first 18 repeating FRBs discovered by CHIME. Figure by Shriharsh Tendulkar.

2.3 Galactic magnetar

Another important result CHIME obtained is the detection of an FRB from a Galactic magnetar. On April 28, 2020, CHIME detected an FRB from magnetar SGR 1935+2154 (CHIME/FRB Collaboration et al. 2020). This event was also noticed by the STARE2 collaboration (Bochenek et al. 2020). The energetics of this burst falls between the FRB and the Galactic pulsar population, potentially providing a path to close the existing energy gap. It is tempting to speculate that all FRBs are produced by magnetars. Indeed, a number of FRB emission models proposed involve magnetars (see, e.g. Metzger et al. 2017). However, some FRBs have now been localized to the outskirts of galaxies (see, e.g. Marcote et al. 2020), whereas Galactic magnetars are preferentially located near the Galactic plane. In addition, the morphology of this FRB from SGR 1935+2154 is somewhat atypical, and it would be premature to conclude that this burst can serve as a representative for all FRBs. Nonetheless, the importance of this discovery has been recognized by the Science magazine which has ranked it one of the most significant breakthroughs in 2020[†], second only to the discovery of the covid vaccine.

2.4 Low-DM FRBs

A few other CHIME FRBs have been localized to their host galaxies. One of them has been associated with M81, a spiral galaxy in the local volume at 3.6 Mpc (Bhardwaj et al. 2021a). The Precise team has further pin-pointed the FRB to be from a Globular Cluster (Kirsten et al. 2021). Another FRB has been found to be from NGC3252 (Bhardwaj et al. 2021b), a star-forming spiral galaxy at 20 Mpc. These two are the nearest localized FRBs so far, apart from the Galactic magnetar FRB mentioned in Section 2.3. These nearby FRBs are particularly interesting, since they allow easier multi-wavelength follow-up observations, and hence this sub-population might provide the best hope in uncovering the origin of FRBs.

3 Localization with outriggers and CHORD

While CHIME has been extremely successful in discovering a large number of FRBs, it lacks the required localization precision to pin-point the exact origin of these extragalactic bursts. The CHIME/FRB Outriggers project is being deployed which will provide baseline of the order of 1000 m and hence greatly improve localization capability. A prototype of the CHIME outrigger has been set up at the Algonquin Radio Telescope, and this system has detected and localized FRBs with a localization uncertainty of tens of milliarcseconds (Cassanelli et al. 2021), a significant improvement over CHIME alone.

Looking ahead, CHORD is a \$20 M experiment (Vanderlinde et al. 2019) whose budget has just been approved by the Canadian Research Council. CHORD will have ultra-wideband receivers covering 300−1500 MHz. It will have a highly sensitive core array consisting of 512 6-m dishes located right next to CHIME as well as multiple outrigger stations. CHORD is expected to provide both the large number of FRB detections as well

[†] `https://vis.sciencemag.org/breakthrough2020/#/finalists/found:-elusive-source-of-fast-radio-bursts`

as milliarcsecond localization capability. CHORD is expected to come online within the next few years and it is a promising instrument to pave the path to use FRB as cosmological probes.

4 Conclusion

The CHIME Catalog 1 consists of 536 FRBs including 18 repeaters. The FRB event rate as determined from the CHIME data is about 800 bursts/sky/day with an Euclidean distribution. FRBs appear to be correlated with galaxy large-scale structure over a wide redshift range. There is evidence that there are multiple FRB populations, notably one-off vs repeating FRBs. These two samples have different burst widths and emission bandwidth distribution. One of the repeaters shows periodicity in its activity cycle, and another one has sub-second periodicity within its multi-component profile. Furthermore, an FRB has been associated with a Galactic magnetar, while some low-DM FRBs have been identified with their host galaxies. The CHIME/FRB Outriggers Project is in progress and will provide better localization capability thanks to the longer baselines. The next step up will be enabled by the CHORD experiment, which is expected to discover thousands of FRBs with milliarcsecond localization, potentially allowing FRBs to be used as cosmological probes.

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