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**Search and multi-frequency follow-up studies of radio transients: novel
approaches and large campaigns**

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Ph.D. Student:	Matteo Trudu
Supervisor	Prof. Andrea Possenti
Co-Supervisor	Dr. Maura Pilia

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**Search and multi-frequency follow-up studies of radio transients: novel
approaches and large campaigns**

Candidate Full Name

Matteo Trudu

Candidate Supervisor

Professor Andrea Possenti

Candidate Advisor

Doctor Maura Pilia

XXXV Cycle Doctoral School Coordinator

Professor Umberto D'Alesio

XXXV Cycle Doctoral School Committee

Professor Biagio Saitta

Professor Michele Saba

Doctor Andrea Sanna

*Fu una bastonata dura per me. Ma poi, che farci? Continuai la mia strada,
in mezzo alle trasformazioni del mondo, anch'io trasformandomi.*

Italo Calvino

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Cagliari, 21 Marzo 2023

Matteo

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Scientific Outputs

Publications as first author:

- **M. Trudu** et al., “*The search for narrow-band FRBs in the High Time Resolution Universe Survey Southern Hemisphere*”, in preparation;
- **M. Trudu** et al., “*Simultaneous and panchromatic observations of the Fast Radio Burst FRB 20180916B*”, under review (A&A);
- **M. Trudu** et al. 2022, “*The Northern Cross FRB Project - II. Monitoring of repeating FRB 20180916B, 20181030A, 20200120E, and 20201124A*”, MNRAS, Volume 513, Issue 2, 1858-1866.

Publications as co-author:

- Borghese et al. 2022, “*The first seven months of the 2020 X-ray outburst of the magnetar SGR J1935+2154*”, MNRAS, Volume 516, Issue 1, 602-616.
- Nimmo et al. 2022, “*Milliarcsecond Localization of the Repeating FRB 20201124A*”, ApJL, Volume 927, Issue 1, L3.
- Piro et al. 2021, “*The fast radio burst FRB 20201124A in a star-forming region: Constraints to the progenitor and multiwavelength counterparts*”, A&A, Volume 656, L15.
- Pilia et al. 2020, “*The Lowest-frequency Fast Radio Bursts: Sardinia Radio Telescope Detection of the Periodic FRB 180916 at 328 MHz*”, ApJL, Volume 896, Issue 2, L40.

At present, Fast Radio Bursts (FRBs) are probably the most intriguing phenomenon in the time domain radio astronomy.

The very first FRB has been discovered in 2007 (FRB 20010724A), in a completely fortuitous way as it happened 40 years earlier this discovery for pulsars, while searching for something different (new rotating radio transients) in archival data. After this isolated discovery, it was only in 2013 that the astronomical community discovered a sample of FRBs, and that finally confirmed their astrophysical nature. Another intriguing consequence of this confirmation was the assessment of the very high rate of these previously missed events, flashing in the sky several thousands of times during a single day.

On an observational ground, the FRBs are bright and highly dispersed radio transients of ms duration. Their large Dispersion Measure (DM) suggested, since the beginning, extragalactic origin (so far there is only one exception to this). To date, they have been detected from very low radio frequencies (around 140 MHz) up to 8 GHz.

So far a total of 625 FRBs have been discovered and an outstanding contribution to this comes from the Canadian Hydrogen Intensity Map Experiment (CHIME) radio telescope: before CHIME started to operate in 2018, only a few dozen of FRB sources were known.

To date, most (600) of the discovered FRBs, seem to be single one-off, *una tantum*, events. However a small fraction (25) of them are *repeating sources*, with at least two detected bursts. The hypothesis that all FRBs are ultimately repeaters still remains unresolved. In addition, two of these repeating sources, FRB 20121102A and FRB 20180916B, have shown to be periodically active, i.e. they produce FRBs within a certain time window (~ 90 days and ~ 5 days, respectively) in a periodic manner (every 160 days and 16 days, respectively). These repeating sources are particularly favourable for targeted observations and, thanks to that, many observational facts have been accumulated: from the identification of their host galaxy (thanks to a precise localisation), to the investigation of the association (if any) with a persistent radio source, to the possibility of studying their very high time resolution properties and thus unveiling their capability to produce strong shots of a mere nanosecond duration.

All of that led to many progresses in the comprehension of these mysterious phenomena, whose origin is however yet to be clarified. Nevertheless, the observational evidences gathered so far seem progressively pointing toward highly magnetised compact objects, such as the magnetars, as the most likely progenitors for at least a subsample of the FRBs.

In this respect, a striking event happened in April 2020. The Galactic magnetar SGR J1935+2154, discovered in 2014, went in an outburst phase emitting a storm of X-ray bursts. One of these

X-ray bursts, detected by the AGILE, *Insight*-HXMT, INTEGRAL and Konus/WIND satellites, happened to be simultaneous with a bright radio burst found by the CHIME and STARE2 radio telescopes, and closely resembling an FRB. Very recently again, in Autumn 2022, this source went very active with simultaneous X-rays/radio detections been reported.

Despite this event bolstered the link between the magnetars and (at least some) FRBs, a multi-wavelength (MWL) detection of an FRB counterpart in the X-ray/ γ -ray (and possibly in the optical/infrared window) would mean either to further strengthen this connection or to show that other classes of astrophysical sources might be responsible for the emission of FRBs. Furthermore, a MWL detection could discriminate emission mechanisms which imply simultaneous multi-wavelength strong bursts across the electromagnetic spectrum, from emission processes which should lead to bursts at other electromagnetic bands before or after the radio emission.

MWL observations of FRBs are indeed the main driver of this PhD Thesis. On the other hand, MWL campaigns strongly depend on the capability to detect bursts in the radio band, which can happen with the deployment of proper instruments and with the use of dedicated search algorithms. In view of that, **the PhD work presented in this Thesis, revolves around the following three main themes:** (i) the analysis and possible improvement of the FRB detection algorithms; (ii) the development of radio facilities tailored for the FRB observations, and lastly (iii) a series of large MWL campaigns targeted to some of the FRB sources.

The Thesis is organised in four Chapters. Each of them, firstly provides a brief review of the state-of-the-art on a particular FRB thematic and secondly reports on an *original contribution* developed during the PhD work.

CHAPTER 1 provides a review of the main observational properties of the FRB phenomenon and a short survey of the main categories of the currently proposed FRB models. As an original contribution, we show that the FRB 20121102A bursts appear to not possess a dependence between the frequency band of occurrence of the bursts and the phase of the window of activity along a cycle. This dependence was shown in literature to be evident for the other yet known periodic FRB, namely FRB 20180916B.

In CHAPTER 2 we initially describe how data are recorded and processed by a radio telescope in the context of the FRB science. We then review the currently used FRB search algorithms. As our original contributions, first we mathematically formalise the so-called *FRB sub-banded searches*, namely the searches performed in a limited portion of the total available observational bandwidth, and showed what signal-to-noise ratio can be gained or lost by running these sub-banded searches. This is motivated by the fact that the FRBs tend to manifest in a relatively narrow frequency band (typical bandwidths of ~ 100 MHz) with respect to the wide bandwidths available to most modern instruments. As a second part of our work, we applied the sub-banded search algorithm to the High Latitude portion of the High Time Resolution Universe (HTRU) survey, which was carried out at the Parkes radio telescope about a decade ago, and led to the discovery of a total of 10 FRBs. As a result of our re-processing with the new approach, we present the detection of 18 new plausible, faint, FRBs, which were missed by the previous full-band searches.

CHAPTER 3 begins with a brief description of the radio telescopes, which are typically used for studying the FRBs. We then introduce the Northern Cross (NC) FRB Project, one of the

main goals of which is to use the NC telescope as an FRB machine. The NC telescope is a T-shaped radio interferometer located in Medicina (Bologna, Italy) and constructed in 1967. As our original contribution, we report the results of the first NC FRB campaign, started in January 2020 and ended in August 2021, which monitored four repeating FRB sources: FRB 20180916B, 20181030A, 20200120E and 20201124A. In particular we will present the first FRB detections (three bursts from FRB 20180916B) obtained with this telescope.

In CHAPTER 4, we focus our attention on the MWL observations of FRBs. We initially review the MWL campaigns reported in the literature, and diffusely discuss the SGR J1935+2154 event with its implications. As our original contribution, we then present the results of a large, year-long, MWL campaign on the periodic FRB 20180916B, which was carried out with the Sardinia Radio Telescope (SRT) and the upgraded Giant Metrewave Radio Telescope (uGMRT). Several optical telescopes were also involved (Asiago telescopes, CMO SAI MSU, CAHA 2.2m, RTT-150 and TNG), as well as X-ray/ γ -ray satellites (AGILE, *Insight-HXMT*, INTEGRAL and Swift). This campaign set the most stringent upper limit to date on the prompt simultaneous emission from a putative optical counterpart to a FRB.

Finally, we summarise the main outcomes from our work, and look at possible developments and perspectives.

A Storm coming from the Radio Sky

This chapter will mainly serve as a review of the phenomenology and models associated to the Fast Radio Bursts. In the first section we will report the historical milestones achieved in the field. In the second section we will discuss the main observed properties of the Fast Radio Bursts. In the third section we will briefly introduce the current families of models available to explain this phenomenon, with an emphasis on the observational constraints. In the fourth section (Sec. 1.4) we will describe an original contribution to the study of the FRB phenomenology: we will show that a periodic source, FRB 20121102A, does not show the chromatic activity which has been observed from the other periodic source FRB 20180916B.

1.1 The Fast Radio Burst Phenomenon

The term “transient-astronomy” refers to a branch of astronomy interested in the study of phenomena happening within a limited duration, which can span from nanoseconds to years. Some of these transient events are *una tantum*, others repeat either in an irregular way or following a periodic pattern. To mention a very few of them, transient phenomena are all the novæ, variable stars, Gamma-ray Bursts (GRBs), Gravitational Waves (GWs), pulsars and the latest class of radio transients, discovered in 2007, called Fast Radio Bursts (FRBs, see e.g. Bailes, 2022; Petroff, Hessels, and Lorimer, 2022; Petroff, Hessels, and Lorimer, 2019, for updated reviews).

1.1.1 Some Historical Remarks

The discovery of the FRBs was a serendipitous process, like that leading to the discovery of the first pulsar by S. J. Bell (PSR B1919+21, Hewish et al., 1968) at the Mullard Radio Observatory 55 years ago.

Pulsars are rapidly spinning neutron stars, born from super novæ, with high magnetic fields whose axis is, in general, not aligned with the rotation axis which emit beamed electromagnetic radiation in a similar fashion as a lighthouse. Because of their beamed radiation, the signal coming from a pulsar recorded by a radio telescope appears to be a periodic

train of pulses, whose time of repetition is driven by the rotational period of the pulsar. This periodic emission was indeed the key which led to the discovery of the first pulsar, PSR B1919+21. In fact, by inspecting the shape of the time series recorded by her pen chart recorder, Bell realised there was an excess of signal in the time series, which repeated at the pace of about one second (1.3372 s).

After her ground breaking discovery, the field of pulsar radio astronomy experienced a never-ending growth, with the follow-up detection of more and more pulsars thanks to new radio telescopes and thanks to the improvement of computers which enabled the use of increasingly more sophisticated search algorithms. Indeed new fascinating objects were discovered after PSR B1919+21, among which a pulsar in a binary system (Hulse and Taylor, 1975), a millisecond-period pulsar (Backer et al., 1982), the first and yet unique double-pulsar system (Burgay et al., 2003; Lyne et al., 2004) and a new class of astrophysical objects called *Rotating Radio Transients* (RRATs, McLaughlin et al., 2006).

RRATs are pulsar-like objects which emit pulses, in phase with the rotation period of the neutron star that produces them. They show a remarkably high pulse-to-pulse variability. The detection of these rarely emitting pulsating sources was possible thanks to the deployment of single pulse searches, based on matched filtering algorithms (Cordes and McLaughlin, 2003; McLaughlin and Cordes, 2003). As opposed to searches for ordinary pulsars (where the techniques are based on Fourier Transforms or Fast Folding algorithms), the single pulse searches were originally introduced in order to search for the so called *Giant Pulses*, a phenomenon of sporadic emission of very strong pulses (more than ten times the mean flux of the ordinary pulses), which is seen in a sub-sample of the pulsars.

In 2007, searching for RRAT sources in the Small Magellanic Cloud (SMC, a dwarf galaxy close to the Milky Way, MW) within archival data of the Parkes telescope in Australia, D. R. Lorimer and collaborators detected a single and extremely bright burst similar to the ones produced by pulsars and RRATs. That detection (Lorimer et al., 2007) turned out to be the first FRB discovered, FRB 20010724A¹. The burst was so powerful to be detected in four adjacent beams of the receiver and it even saturated the detector, causing a change on the noise baseline right after the pulse occurred (see the time series in Fig. 1.1). After this discovery, searches for similar events started, both through digging of archival data (Bagchi, Nieves, and McLaughlin, 2012; Burke-Spolaor and Bailes, 2010) and through new surveys (Lynch et al., 2013; Siemion et al., 2012) but none of these efforts was successful in identifying a candidate classifiable as an FRB event. This increased scepticism around a true astrophysical origin of the *Lorimer Burst* (LB). In fact, in the same years similar interesting sources were found by the Parkes telescope, which were dubbed perytons (Burke-Spolaor et al., 2011). Very soon after their discovery, however, the scientific community realised they were radio frequency interference (RFI), specifically coming from a micro-wave oven (Petroff et al., 2015b).

Finally, in 2013, four new FRBs (Thornton et al., 2013) were found by processing a fraction of the survey High Time Resolution Universe (HTRU) from Parkes (Keith et al., 2010), disambiguating in a definitive way the astrophysical nature of the LB and showing that it is part of a new population of astrophysical objects. Thereafter, they were called Fast Radio Bursts.

The HTRU discovery started a flourishing era for FRBs with several milestones reached in the subsequent years: the discovery of FRB 20121102A by Arecibo in Puerto Rico (Spitler

¹In this thesis we will use the Transient Name Server (TNS) convention to name FRB sources as FRB YYYYMMDDxxx, where YYYY is the year, MM the month, DD the day, and xxx are letters from A to Z to order FRB events happened in the same day.

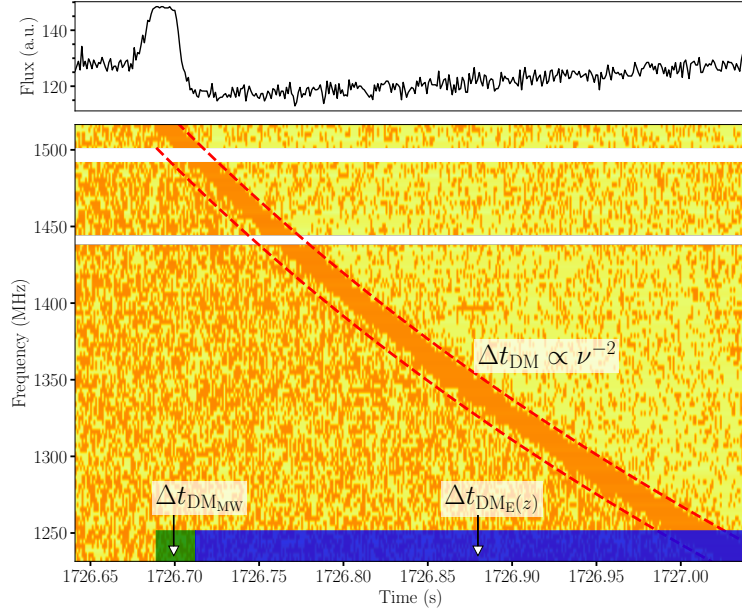


Figure 1.1: Re-plotting of the first FRB ever discovered, FRB 20010724A (also called the *Lorimer Burst*, Lorimer et al., 2007). The top panel shows, the frequency averaged time series corrected by the delay due to the dispersion effect ($DM = 375 \text{ pc cm}^{-3}$). The bottom panel represents the spectrogram of the signal, not corrected for the dispersion delay. From the spectrogram it is clearly visible the sweep of the signal along the frequency axis, delayed according to Eq. 1.7. The green bar at the bottom of the spectrogram shows the expected delay if the burst had a DM close to the expected total Milky Way contribution in that direction of the sky ($DM_{\text{MW}} \sim 25 \text{ pc cm}^{-3}$, Cordes and Lazio, 2002) and the blue bar represent the residual delay contribution due to the excess in $DM_{\text{E}} \sim 350 \text{ pc cm}^{-3}$. The blank rows are excised frequency channels due to the presence of radio frequency interference.

et al., 2014) which happened to be the first FRB to repeat (Spitler et al., 2016); its localisation with a milliarcsecond precision (Chatterjee et al., 2017; Tendulkar et al., 2017; Marcote et al., 2017), being the first FRB localisation, and placing the source in a dwarf galaxy at a distance of about 1 Gpc; the assessment of a periodic activity of about sixteen days from FRB 20180916B (Chime/FRB Collaboration et al., 2020) lately found also in FRB 20121102A (~ 160 days, Rajwade et al., 2020); the emission from the Galactic magnetar SGR J1935+2154 of an FRB-like signal simultaneously detected in the X-rays (The CHIME/FRB Collaboration et al., 2020; Bochenek et al., 2020a; Mereghetti et al., 2020; Zhang et al., 2020b; Ridnaia et al., 2020; Tavani et al., 2020a) and many other results that we will discuss in this Thesis. Up to date, 625 FRBs have been discovered with only 25 of them being repeaters, two of which being also periodically active. 23 FRBs (both repeaters and one-off FRBs) have been accurately localised, with an associated host galaxy; one of them has been localised in a globular cluster of its host galaxy. Figure 1.2 shows an updated sky distribution of the FRBs detected so far. It is worth noticing the remarkable contribution provided by the Canadian Hydrogen Intensity Mapping Experiment (CHIME, CHIME/FRB Collaboration et al., 2018) telescope: after it started its operations in 2018, the number of known FRBs has increased by more than an order of magnitude, from a few dozen to several hundred.

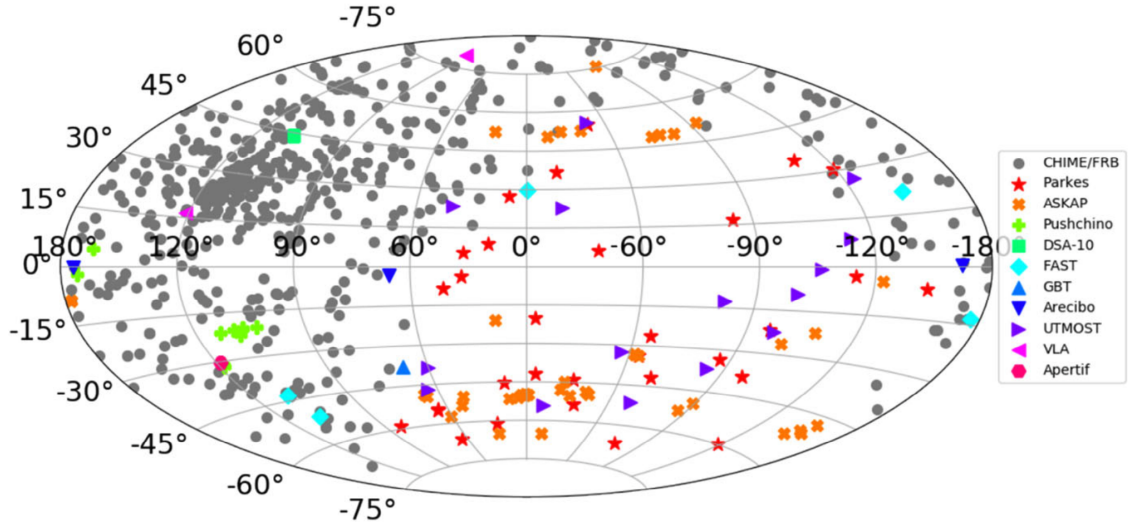


Figure 1.2: Sky distribution (Aitoff projection) of the sample of the FRBs discovered to date. Image from Petroff, Hessels, and Lorimer (2022).

1.2 Properties of Fast Radio Bursts

1.2.1 Dispersion

The LB, depicted in Fig. 1.1, is very insightful to introduce some basic properties of an FRB signal. Some of these properties are common properties among FRBs, pulsars and RRATs. From Fig. 1.1 the first peculiarity from the spectrogram of the observation (bottom panel) is that the signal, in each frequency channel, is delayed of an amount which scales as the inverse-square of the frequency ν of the channel. This is due to a physical effect, called **dispersion**, which affects any electromagnetic (EM) wave propagating in an ionised medium.

In general the EM waves of an astrophysical source interact with the intervening medium, which can be the interstellar medium (ISM) for a signal coming from the MW or, in addition to the ISM, the intergalactic medium (IGM) and the ISM of the host galaxy for a signal coming from outside our Galaxy.

An EM wave, in vacuum, travels with the speed of light c , as seen by solving Maxwell's equations. In the case of an EM wave propagating in a medium, the radiation propagates with the group velocity v_g which can be expressed as:

$$v_g(\nu) = n(\nu)c, \quad (1.1)$$

$n(\nu) \leq 1$ is the *refractive index*, a function of the frequency of the signal which captures the macroscopic properties of the interacting medium. Since in our case the medium is a cold ionised plasma, we can parameterise the refractive index as (Lorimer and Kramer, 2005; Rybicki and Lightman, 1986):

$$n(\nu) = \sqrt{1 - \left(\frac{\nu_p}{\nu}\right)^2}, \quad (1.2)$$

where ν_p is the *plasma frequency*

$$\nu_p = \sqrt{\frac{e^2 n_e}{\pi m_e}} = 8.5 \times \left(\frac{n_e}{\text{cm}^{-3}}\right)^{1/2} \text{ kHz}. \quad (1.3)$$

The constants e, m_e are the elemental charge and the electron mass and n_e is the electron number density of the medium. When travelling to the Earth each spectral component ν of the EM wave will experience a delay with respect to a signal at infinite frequency² by an amount

$$t_\nu = \int_0^d \frac{1}{v_g(\nu)} dl - \frac{d}{c}, \quad (1.4)$$

where d is the distance of the source. Since, typical electron densities $n_e \ll 1 \text{ cm}^{-3}$ and since the lowest frequency observations in FRB astronomy are performed at the order of a few hundred of MHz we can assume that $\nu \gg \nu_p$. Substituting now Eq. 1.1 for v_g and Taylor expanding Eq. 1.2 at the first order we have for Eq. 1.4:

$$\begin{aligned} t_\nu &= \frac{1}{c} \int_0^d \frac{1}{n(\nu)} dl - \frac{d}{c} \simeq \frac{1}{c} \int_0^d \left(1 + \frac{\nu_p^2}{2\nu^2} \right) dl - \frac{d}{c} \\ &= \frac{1}{c} \int_0^d \frac{\nu_p^2}{2\nu^2} dl \\ &= \frac{e^2}{2\pi m_e c \nu^2} \int_0^d n_e(l) dl \\ &:= \mathcal{D} \frac{\text{DM}}{\nu^2}, \end{aligned} \quad (1.5)$$

where we define a quantity called **dispersion measure**

$$\text{DM} = \int_0^d n_e(l) dl, \quad (1.6)$$

which is measured in pc cm^{-3} and $\mathcal{D} = e^2/(2\pi m_e c) \simeq 4.15 \times 10^3 \text{ MHz}^2 \text{ pc}^{-1} \text{ cm}^3 \text{ s}$ is the *dispersion constant*. From Eq. 1.6 we see that the DM represents the integral along the line of sight of the free electrons. As we will see in Chap. 2, the knowledge of the DM is crucial when performing FRB analysis.

When observing a signal between two frequencies ν_a, ν_b , the total delay Δt_{DM} due to the dispersion effect can be computed by Eq. 1.5:

$$\begin{aligned} \Delta t_{\text{DM}} &= t_{\nu_a} - t_{\nu_b} = \mathcal{D} \text{DM} \left(\frac{1}{\nu_a^2} - \frac{1}{\nu_b^2} \right) \\ &\simeq 4.15 \times 10^6 \times \left(\frac{\text{DM}}{\text{pc cm}^{-3}} \right) \left[\left(\frac{\nu_a}{\text{MHz}} \right)^{-2} - \left(\frac{\nu_b}{\text{MHz}} \right)^{-2} \right] \text{ ms}. \end{aligned} \quad (1.7)$$

When the FRB pulses or the single pulses from a pulsar/RRAT are particularly strong in theory one can infer the DM by measuring the sweep of the signal and then using Eq. 1.7. This, however, only applies to rare cases, as it is difficult to see the dispersed signal in the spectrogram most of the time. The DM is rather inferred by trials, using a technique called *dedispersion*. The signal, in the spectro-temporal domain is aligned in time, for each frequency channel, according to Eq. 1.7 using a number of DM trials and then the signal-to-noise ratio (S/N) of the frequency averaged time series is computed. When the signal is corrected with the right DM, the S/N of the time series will be at its maximum (see Fig. 2.1). We lastly point out, to be more precise, the technique previously mentioned is defined incoherent dedispersion and it will be discussed in more detail in Chap. 2 in the data processing section.

²From Eq. 1.2 we see that an EM wave at $\nu = \infty$ is equivalent to a wave propagating in vacuum ($n = 1$).

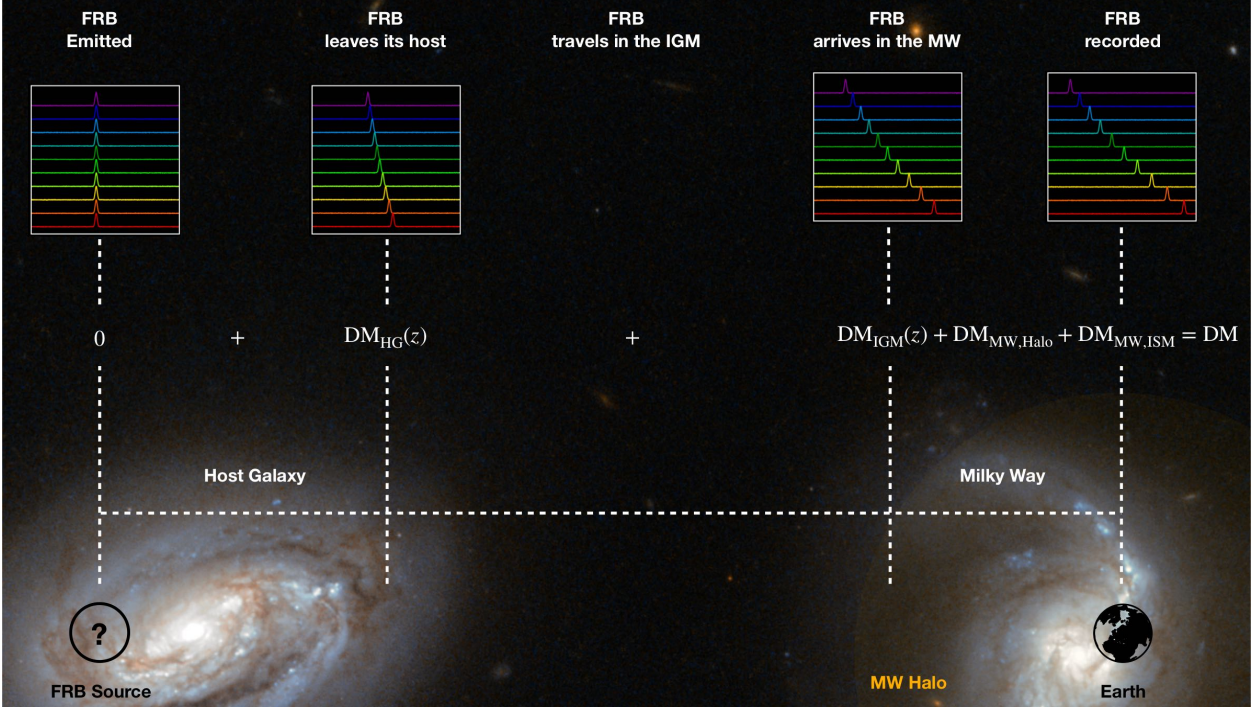


Figure 1.3: The DM contributions to the total DM of a typical FRB. An FRB emitted, by an unknown source, is locally at $DM = 0 \text{ pc cm}^{-3}$. After it crosses the edge of its host galaxy (HG) the FRB signal is dispersed by an amount $DM_{HG}(z)$. The signal then travels through the whole intergalactic medium (IGM) between the HG and the Milky Way (MW). After having reached the outskirts of the MW, the signal is dispersed by an amount $DM_{HG}(z) + DM_{IGM}(z)$. Lastly the FRB reaches the Earth and it is recorded by a radio telescope. At this point the signal is dispersed by a total amount as reported in Eq. 1.8. The distances are not to scale. The background image used for this cartoon is the pair of galaxies MRK 1034 (Credits: ESA/Hubble & NASA, <https://esahubble.org/images/potw1325a/>).

In the case of the MW, there are models which map the electron density distribution n_e within our Galaxy. On the basis of these models, one can guess the value of the DM for a pulsating source located within our Galaxy at a given distance and along an assigned line-of-sight, or, vice versa, one can predict the distance for a given DM and line-of-sight. The most established models are the NE2001 (Cordes and Lazio, 2002) and the YMW16 (Yao, Manchester, and Wang, 2017) models. Despite their predictions can be very inaccurate for one specific source, the typical error bar in the “DM vs distance” relation is of order 50% of the predicted values when applied to a large population.

1.2.2 Extra-Galactic ?

From the LB in Fig 1.1 we notice that the signal is delayed (in the observational band of 1231 – 1516 MHz) of about 0.34 s. This, from Eq. 1.7, implies $DM \sim 375 \text{ pc cm}^{-3}$ as indeed reported in Lorimer et al. (2007). NE2001 DM predictions for the direction of the LB gives a value of $\sim 25 \text{ pc cm}^{-3}$ and the Galactic latitude of the LB is $b = -41.8^\circ$, which places it quite far from the Galactic plane. Furthermore, none of the pulsars discovered in the SMC possess a DM compatible with the LB, with the highest being PSR J0131-7310 (with $DM = 205 \text{ pc cm}^{-3}$, Manchester et al., 2006) which is expected to reside in a HII region of the SMC. Even supposing that the LB originated from an HII region of the SMC its DM

should be about half its measured value. This finding strongly suggested that the LB had to be originated outside our Galaxy and the SMC.

In the whole sample of the 625 bursts discovered to date, apart the aforementioned case of the Soft Gamma Repeater (SGR) J1935+2154 which we will discuss separately, the measured DM is far greater than the predicted Galactic DM contribution. Moreover the 23 FRB sources with accurate position so far have been localised in galaxies outside the MW (red-shifts $0.0001 < z < 0.66$), with the closest FRB (FRB 20200120E, Bhardwaj et al. 2021b) localised in the M81 galaxy at 3 Mpc (Kirsten et al., 2022). These facts suggest the extra-galactic origin as the most plausible scenario for the FRB seen and catalogued so far.

Since the DM is an integral of the electron density, we can exploit the summation property of the integrals and write the DM as the sum of several contributions:

$$\text{DM} = \text{DM}_{\text{MW,ISM}} + \text{DM}_{\text{MW,Halo}} + \text{DM}_{\text{IGM}}(z) + \text{DM}_{\text{HG}}(z) . \quad (1.8)$$

We discuss now each contribution separately, going in order from the Earth to the source:

- $\text{DM}_{\text{MW,ISM}}$: this contribution is due to the ISM of our Galaxy and, as already mentioned, it can be reasonably evaluated by using the NE2001 or YM16 models.
- $\text{DM}_{\text{MW,Halo}}$: this contribution comes from the ionised gas diffuse in MW Halo, Prochaska and Zheng (2019) estimated this contribution to be about $50 - 80 \text{ pc cm}^{-3}$.
- $\text{DM}_{\text{IGM}}(z)$: this is the contribution of the IGM, along the line-of-sight. Very importantly, we can write its functional dependence on the cosmological red-shift z , assuming a flat Universe, in the following way (Macquart et al., 2020; Deng and Zhang, 2014; Inoue, 2004; Ioka, 2003):

$$\text{DM}_{\text{IGM}}(z) = \int_0^z \frac{cf_e(z')}{H_0 (1+z')^2 \sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}} dz' , \quad (1.9)$$

where H_0 is the Hubble constant, Ω_M and Ω_Λ are the dark matter and dark energy densities respectively and

$$f_e(z) = \rho_d(z) \Omega_b \frac{(1 - Y_{\text{He}}/2)}{m_p} \rho_c (1+z)^3 . \quad (1.10)$$

The function $\rho_d(z)$ is the fraction of cosmic baryons in the diffused ionised gas of the IGM, Ω_b is the baryon density, Y_{He} is the mass fraction of helium, m_p is the proton mass, and $\rho_c = 3H_0^2/(8\pi G)$ is the critical density of the Universe.

- $\text{DM}_{\text{HG}}(z)$: the last contribution is the DM of the host galaxy of the FRB source. This contribution is, in general, poorly constrained and we assume that DM_{HG} is comprehensive of the ISM of the host, of the ionised gas in the host halo and the local environment of the source. Being at cosmological distances, this contribution is usually parameterised as

$$\text{DM}_{\text{Host}}(z) = \frac{\text{DM}_{\text{Host}}}{(1+z)} , \quad (1.11)$$

where DM_{Host} is the intrinsic host contribution. We note that, for large distances, this contribution becomes negligible and the only dominant DM excess from the Galactic contribution comes from the IGM.

Figure 1.3 depicts a cartoon which describes how an FRB signal is delayed by the DM contribution of the obstructing matter between the source and the Earth. Each frequency component is codified with a rainbow colour scale, from the highest frequencies (violet) to the lowest ones (red). When the FRB signal is emitted by its source it has $DM = 0 \text{ pc cm}^{-3}$ and each frequency component is aligned in time. After it crosses the edge of its host galaxy, the signal is smeared by $DM_{\text{HG}}(z)$. After the FRB travelled the interposed IGM, the signal is dispersed by an amount $DM_{\text{HG}}(z) + DM_{\text{IGM}}(z)$ reaching the outskirts of the MW. Lastly the FRB gets to the Earth, and the recorded signal (between the two observational frequencies of the instrument) is delayed according to Eq. 1.8.

Using Eq 1.8, and estimating the Galactic contribution, one can have an estimate of the red-shift of the FRB and, henceforth, of its distance. By using Eqs. 1.9, 1.11, if one makes some assumptions on the host galaxy DM_{HG} and considers an average value for the MW contribution, one can find a reasonable formula for an upper limit distance d (more precisely the luminosity distance, see e.g. Hogg 1999) of the FRB as function of solely the observed DM for $z < 1$ (Petroff, Hessels, and Lorimer, 2019):

$$d < \left(\frac{DM}{500 \text{ pc cm}^{-3}} \right) \left[\left(\frac{DM}{1000 \text{ pc cm}^{-3}} \right) + 2.4 \right] \text{ Gpc} . \quad (1.12)$$

1.2.3 Scattering

The dispersion is not the only external phenomenon which can affect an FRB signal. In fact, if the medium is not homogeneous and it shows anisotropies and turbulences, other effects come into play, such as the *scattering*.

The density irregularities of the interacting medium cause a multi-path propagation of the FRB signal implying a later time of arrival for parts of the signal that travel along longer paths. As a result, these delayed signal components create a “tail” in the pulse profile. A simple model to describe scattering is the thin-screen model (Scheuer, 1968), which assumes that the medium irregularities follow a Komolgorov spectrum and are confined in a thin layer between the source and the observer. It can be shown (Lorimer and Kramer, 2005, Chap. 4) that the recorded intensity of the signal is modulated by an exponential decay e^{-t/τ_s} , where τ_s is called *scattering time*. The scattering time determines how much the FRB signal is exponential-decay broadened (see Fig. 1.4) and it depends on the frequency of the signal as:

$$\tau_s \propto \nu^{-4} . \quad (1.13)$$

1.2.4 Scintillation

Similarly to the case of the scattering, the medium inhomogeneities cause also the so-called *scintillation*, which manifests as in intensity fluctuations of the FRB signal (see the right panel of Fig. 1.4). Scintillation is due to the constructive/destructive sum of the signal wave fronts at the location of the observer’s, creating an interference pattern. In order for the interference to effectively occur within a bandwidth $\Delta\nu_s$ (called *scintillation bandwidth*), the following condition must apply (Lorimer and Kramer, 2005, Chap. 4):

$$2\pi\Delta\nu_s\tau_s \sim 1 , \quad (1.14)$$

thus the scintillation bandwidth scales a ν^4 .

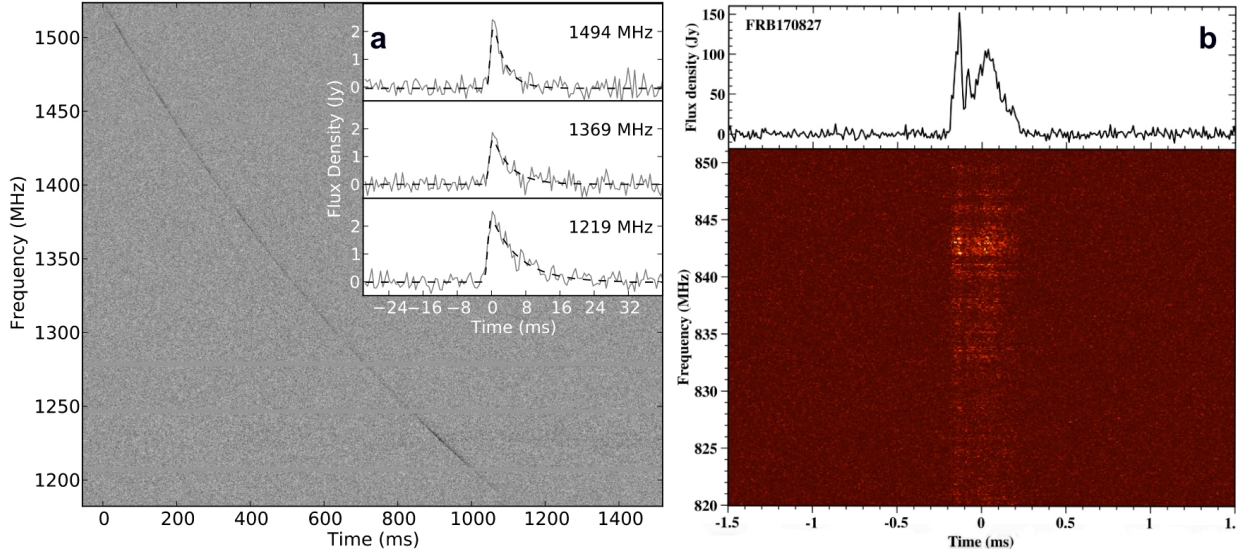


Figure 1.4: Example of an FRB in which a clear scattering broadening is visible (a), FRB 20110220A (image adapted from Thornton et al., 2013), and another FRB, FRB 20170827A (image adapted from Farah et al., 2018), where it is possible to appreciate the scintillation effect in the FRB spectrogram (b).

1.2.5 Burst Temporal Width

The observed width of an FRB, that is its duration, is usually of the order of ms. However, several effects could affect the detected width, by broadening an intrinsically narrower pulse. Some of them due to physical effects (as the ones mentioned above) and some of them due to instrumental factors. Often an FRB appears in the time domain as a single Gaussian function-like pulse although some of them possess more complex structures as we will discuss later. The observed pulse width Δt , considering all the broadening effects, can be expressed as (Lorimer and Kramer, 2005):

$$\Delta t = \sqrt{\Delta t_i^2 + dt^2 + \delta t_{\text{DM}}^2 + \delta t_{\text{DMerr}}^2 + \tau_s^2}, \quad (1.15)$$

where Δt_i is the intrinsic width of the burst, dt is the time resolution of the acquired time series, δt_{DM}^2 is the dispersion delay across a single frequency channel (see Sec. 2.1.1 for more details), $\delta t_{\text{DMerr}}^2$ is a residual broadening due to the uncertainty of the DM measure and τ_s is the scattering time scale.

The measure of Δt is quite important, because it allows us to already make some basic constraints on the size of the progenitors. In fact, for simple causality reasons, the size of the region l from where a burst originates has to be $l \leq c\Delta t$. In the case of the LB, which lasted for about 5 ms, the emission region was as large as 1500 km at most. This scale length is compatible, for instance, with the extension of the rotating magnetic fields of a neutron star (NS), or with the size of the shocks resulting from the explosions of relativistic objects.

1.2.6 Flux Density and Fluence

In order to characterise the energy emitted by an FRB, the first step is to compute the fluence of the burst(s). If the FRB time series is calibrated and expressed as a flux density $S(t)$ (energy per unit of time, surface, and frequency band, measured usually in Jy), the

fluence F is defined as the integral of $S(t)$ over the width of the burst:

$$F = \int_{\text{on pulse}} S(t) dt . \quad (1.16)$$

Fluences are usually reported in Jy ms. To date, FRB reported fluences span from few hundredth of Jy ms to several hundreds of Jy ms. The calibrated time series $S(t)$ is usually obtained exploiting the *radiometer equation* which can map the time series recorded by a radio telescope into physical meaningful quantities. In particular, the noise fluctuation (standard deviation) σ of the recorded time series can be estimated by a combination of some telescope parameters in the following manner (Lorimer and Kramer, 2005):

$$\sigma \simeq \frac{(T_{\text{sys}} + T_{\text{sky}})}{G \sqrt{N_p} BW \Delta t} , \quad (1.17)$$

where G is the antenna gain, N_p is the number of recorded polarisations (either one or two) of the EM field, BW is the observational bandwidth of the telescope, T_{sys} is the system temperature of the antenna and T_{sky} is the temperature of the sky in the direction of the antenna pointing. The sky temperature can be evaluated for instance from Reich and Reich (1988). Once the time series is set to zero-mean and normalised, obtaining a S/N curve, the calibrated time series can be computed by multiplying the S/N time series by the radiometer noise σ .

1.2.7 Luminosity and Energy

Once the luminosity distance d has been inferred, for instance by using Eq. 1.12, and the fluence F of a burst has been assessed with Eq. 1.16, it is possible to constrain the isotropic luminosity L of the burst. If the burst has a frequency width $\Delta\nu$, the luminosity L of the FRB can be computed (assuming a flat spectrum source) as:

$$L = 4\pi d^2 \frac{F \Delta\nu}{\Delta t} , \quad (1.18)$$

where Δt is the burst time width, computed by Eq. 1.15. Then one can compute the isotropic energy E as the product between the luminosity and the burst width obtaining:

$$E = L \frac{\Delta t}{(1+z)} = 4\pi d^2 \frac{F \Delta\nu}{(1+z)} , \quad (1.19)$$

where the factor $(1+z)$ is introduced to compensate the cosmological time-dilatation effects. FRB typical luminosities are in the range of $10^{38} - 10^{46} \text{ erg s}^{-1}$. It is worthwhile making a comparison with pulsars and RRATs. Figure 1.5 shows a plot by Bailes (2022) of the *transient space* (luminosity as function of the pulse width) of some transients phenomena (pulsars, RRATs, some repeating FRBs, etc.) discovered so far. Despite pulsars and RRATs possess comparable flux densities of the order of Jy and in general comparable widths of the order of ms from Fig. 1.5 we see that, for instance, the LB was $\sim 10^{13}$ more powerful than the average pulsar or RRAT burst. It is known that some pulsars with high magnetic field and/or with short period, occasionally emit Giant Pulses. But even events like the Giant Pulses from the Crab pulsar (Staelin and Reifenstein, 1968) or even its strong flashes found at nanosecond time resolution (Hankins et al., 2003) are orders of magnitude less powerful than the LB. It is interesting to notice that the closest FRB localised, FRB 20200120E is the only FRB with bursts showing a power similar to the Crab nano-shots. Moreover, similarly to the Crab pulsar, these pulses were found via an ultra high time resolution (nanosecond) analysis (Nimmo et al., 2021a).

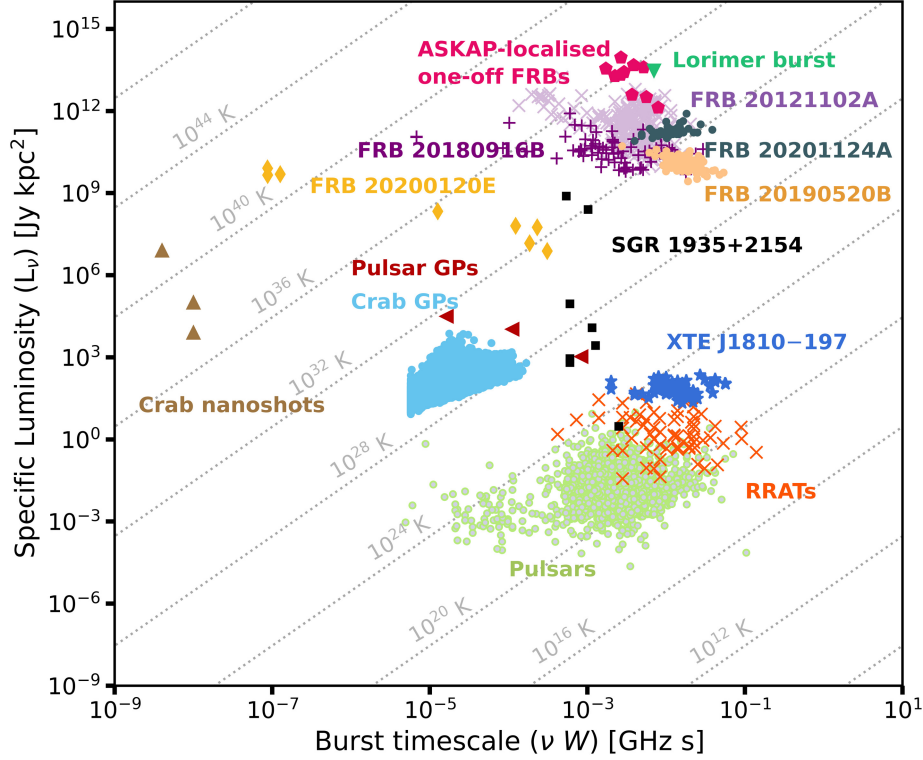


Figure 1.5: Specific luminosity as function of the burst time scale for some of the key transients discovered up to date. Image from Bailes (2022).

1.2.8 Brightness Temperature

In order to characterise the emission of an astrophysical signal, it is quite convenient to introduce the *brightness temperature* T_B , being defined as the temperature of an equivalent black-body emitting with the same intensity I_ν as the radiation from the source. Using the Rayleigh-Jeans approximation $h\nu \ll \kappa T_B$, where h is the Planck's constant and κ is the Boltzmann's constant, we can relate the intensity to the brightness temperature as:

$$I_\nu = \frac{2\nu^2 \kappa T_B}{c^2}. \quad (1.20)$$

We can now relate the intensity as function of the peak flux density S as $I_\nu \sim S/\Omega$, where $\Omega \sim (c\Delta t(1+z)^2/d)^2$ is a proxy to the solid angle subtended by the source. Substituting these expressions in Eq. 1.20 we can express the brightness temperature T_B as:

$$T_B \simeq \frac{Sd^2}{2\kappa\nu^2\Delta t^2} \simeq 10^{36} \times \left(\frac{S}{\text{Jy}}\right) \left(\frac{\nu}{\text{GHz}}\right)^{-2} \left(\frac{\Delta t}{\text{ms}}\right)^{-2} \left(\frac{d}{\text{Gpc}}\right)^2 \text{ K}. \quad (1.21)$$

From Eq. 1.21 we see that FRBs possess remarkably high brightness temperatures, being in the range of $10^{36} - 10^{40}$ K. These high values cannot be ascribed to incoherent emissions, since the maximum brightness temperature for incoherent emission is of the order of 10^{12} K (Kellermann and Pauliny-Toth, 1969). The only possible emission mechanism capable to reach such high temperature is the *coherent emission*. That also happens in pulsars and RRATs, but they display much lower values of T_B , typically in the range $\sim 10^{20} - 10^{30}$ K.

1.2.9 Repeaters

As anticipated in Sec. 1.1.1 some FRBs showed to repeat, that is more than a single burst has been detected. Most of the FRBs detected are single, one-off, events and as we said only 25 of the 625 discovered to date are repeating FRBs (rFRBs or *repeaters*). The first FRB to be found to repeat is FRB 20121102A, initially discovered as a single event at Arecibo (Spitler et al., 2014), while lately, after follow-up campaigns by the same telescope, 10 new bursts (see Fig. 1.6) were detected (Spitler et al., 2016). It is difficult to study one-off FRBs in depth, as follow-up observations are disfavoured, and real-time capabilities are required in order to localise them (the first one-off event was localised in a MW-like galaxy by ASKAP, Bannister et al., 2019) or to search for simultaneous multi radio-band or even multi-wavelength events. The rFRBs, on the other hand, allow us to more easily perform follow-up observations in radio and/or in other frequencies.

Indeed, FRB 20121102A was (and still it is) an amazing laboratory. Thanks to its repetitions FRB 20121102A was localised independently with the Karl G. Jansky Very Large Array (VLA) and the European Very Long Baseline Interferometer (VLBI) Network (Chatterjee et al., 2017; Tendulkar et al., 2017; Marcote et al., 2017) in a dwarf galaxy, luminosity distant of 972 Mpc, of mass $\sim 4 \times 10^7 M_{\odot}$ with a star formation rate of $\sim 0.4 M_{\odot} \text{ year}^{-1}$ and an elemental abundance suggesting that it is at the beginning of its star forming phase. Furthermore this FRB appears to be coincident with a persistent radio source (PRS, Chatterjee et al., 2017; Tendulkar et al., 2017; Marcote et al., 2017). Additional observations with Arecibo and the Robert C. Byrd Green Bank Telescope (GBT), showed that the rotation measure RM^3 for this source is $\sim 10^5 \text{ rad m}^{-2}$ (Michilli et al., 2018). This implies that FRB 20121102A resides in an environment extremely magnetised, rich of free-electrons, similar to that measured for the central region of the MW, where a super massive BH resides. Follow-up observations of FRB 20121102A detected 93 bursts at 6 GHz (Gajjar et al., 2018; Zhang et al., 2018) showing that the source favours emission at GHz frequencies, rather than hundreds of MHz, as supported by the single detection occurred at $< 1 \text{ GHz}$ (600 MHz) by CHIME (Josephy et al., 2019). This was further confirmed with a plethora of bursts detected at the GHz frequencies (almost 1650 bursts detected) by the Five hundred meter Aperture Spherical Telescope (FAST, Li et al., 2021) with some of them clustered into hour-long events, capable to produce “showers” or rains of hundreds of bursts, as also noticed by Jahns et al. (2022) and Hewitt et al. (2021), making FRB 20121102A the most active FRB source to date.

Of the 25 confirmed rFRBs, 21 of them were found by CHIME (Bhardwaj et al., 2021b; Fonseca et al., 2020; CHIME/FRB Collaboration et al., 2019b; CHIME/FRB Collaboration et al., 2019a): another particular FRB, FRB 20180916B (as we will discuss in Sec. 1.2.12), proved to be a particularly fascinating source, as much as FRB 20121102A.

1.2.10 Burst Frequency Width

FRBs, at the best of our current knowledge, appear to have typical frequency widths $\Delta\nu$ in the range of few hundreds of MHz (see e.g. the catalogue of FRBs published by CHIME,

³The rotation measure RM is a quantity accounting for the effect due to the interaction of the EM waves with an ionised and magnetised medium. The parallel component of the magnetic field $B_{\parallel}$ causes a rotation of the linear polarisation angle ψ of the EM field (Faraday Rotation). It can be shown (Lorimer and Kramer, 2005, Chap. 4) that the variation of the polarisation angle $\Delta\psi$ can be written as $\Delta\psi = \lambda^2 \text{RM}$, where λ is the wavelength of the EM radiation and RM is the rotation measure, which is the integral of $B_{\parallel}$ times the electron density number along the line of sight. Hence RM measurements are very powerful as they can be used to probe the magnetic field of the medium.

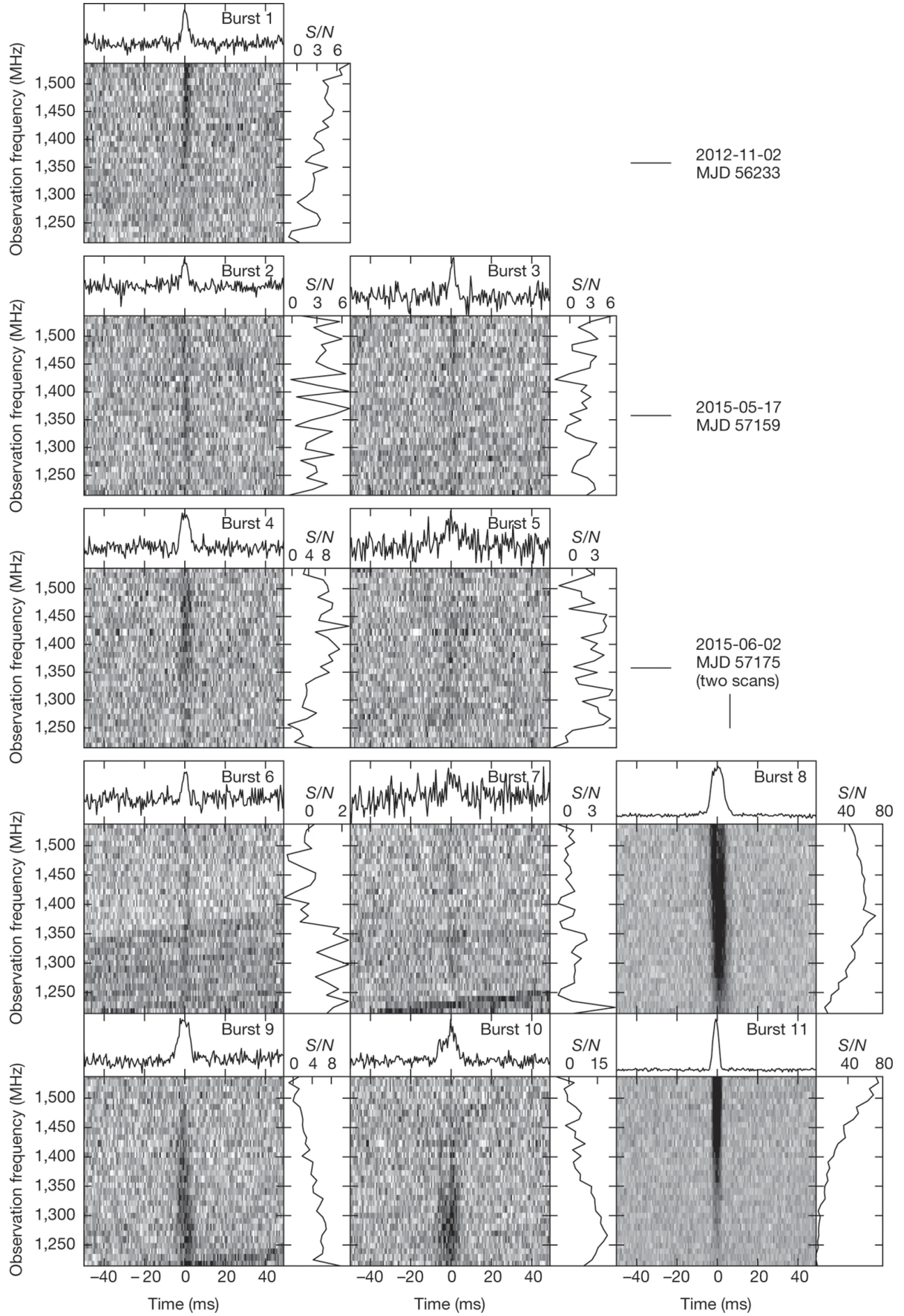


Figure 1.6: The first repeating FRB, FRB20121102A (image from Spitler et al., 2016), proving that FRBs are not only single one-off events. Burst 1 was the initial lone burst detected in Spitler et al. (2014).

The CHIME/FRB Collaboration et al., (2021). A single exception of this comes from FRB 20121102A: a burst from this source was observed on MJD 57648 both by Arecibo at 1.5 GHz and by the VLA at 3GHz (Law et al., 2017). However, the signal strength was not the same in the two bands, since the flux density measurement by Arecibo was an order of magnitude less than the one measured by VLA.

A very extreme opposite example, showing how much FRBs can be narrow-band, comes from a burst from the rFRB FRB 20190711A detected with the ultra wide-band low (UWL) receiver of Parkes: the burst detected (see Fig. 1.7) covers about 2% of the whole observational bandwidth (0.7 – 4.0 GHz) having $\Delta\nu \sim 65$ MHz. This fact poses crucial challenges about the way the searches are made, as we will discuss in detail in Chap. 2. It is worth to mention that recently Geyer et al. (2021) detected giant pulses from PSR J0540-6919 which display frequency widths comparable to the ones from the FRBs.

1.2.11 Burst Complex Structure

When looking at the FRBs in the spectro-temporal domain, that is in their spectrograms, some bursts resemble single 2D Gaussian functions, others show more complex structures. In fact, some of them shows multi-component bursts which appear and disappear at different times and covering different frequency regions of the spectrogram. This frequency positioning of these sub-pulses typically follows a decreasing linear trend (see e.g. Fig. 1.8), called often “sad trombone effect”. Hessels et al. (2019) pointed out that this effect is more prominent at lower frequencies, that is the linear drift rate increases-in absolute value- as we go to lower and lower frequencies.

In view of such complex structures, the DM assessment that we discussed in Sec. 1.2.1 results to be sometimes a tricky task to be performed: in fact, finding the best DM by maximising the S/N can over-dedisperse the signal. In order to properly find the DM which “leaves intact” a possible FRB complex structure, several techniques have been proposed. CHIME/FRB Collaboration et al. (2019b) proposes a coherent summation of the Fourier transformed spectra⁴, while Josephy et al. (2019), Hessels et al. (2019), and Gajjar et al. (2018) suggest to maximise the n -th time-derivative of the dedispersed burst profile for different DM trials with $n = 1, 2, 4$ for each respective reference.

This effect seems to be more common among rFRBs, although we need to be careful with respect to a possible observational bias: one-off bursts are usually detected in large surveys with compromising frequency-time resolutions whereas rFRBs are searched by follow-up observation with higher resolution.

Recent results reported at the FRB 2022 meeting (August 2022), showed a sample of one-off FRBs for which the raw voltage (see Chap. 2 to have more details how FRB data are recorded) data were available, and therefore a high-resolution analysis of these bursts was possible. The recorded bursts showed complex structures with sub-bursts downward drifting (with drift rate furthermore non linear). This shows that it is premature to draw conclusions about the differences in the burst structure between one-off FRBs and rFRBs.

1.2.12 Periodic Activity of rFRBs

Out of the 25 discovered rFRBs, two showed an outstanding property: they possess a periodic activity (periodic FRBs, pFRBs). That is, the source is active for a certain window W_a of time and these activity windows take place cyclically, with a period P_a .

⁴See the software package DM_phase https://github.com/danielemichilli/DM_phase.

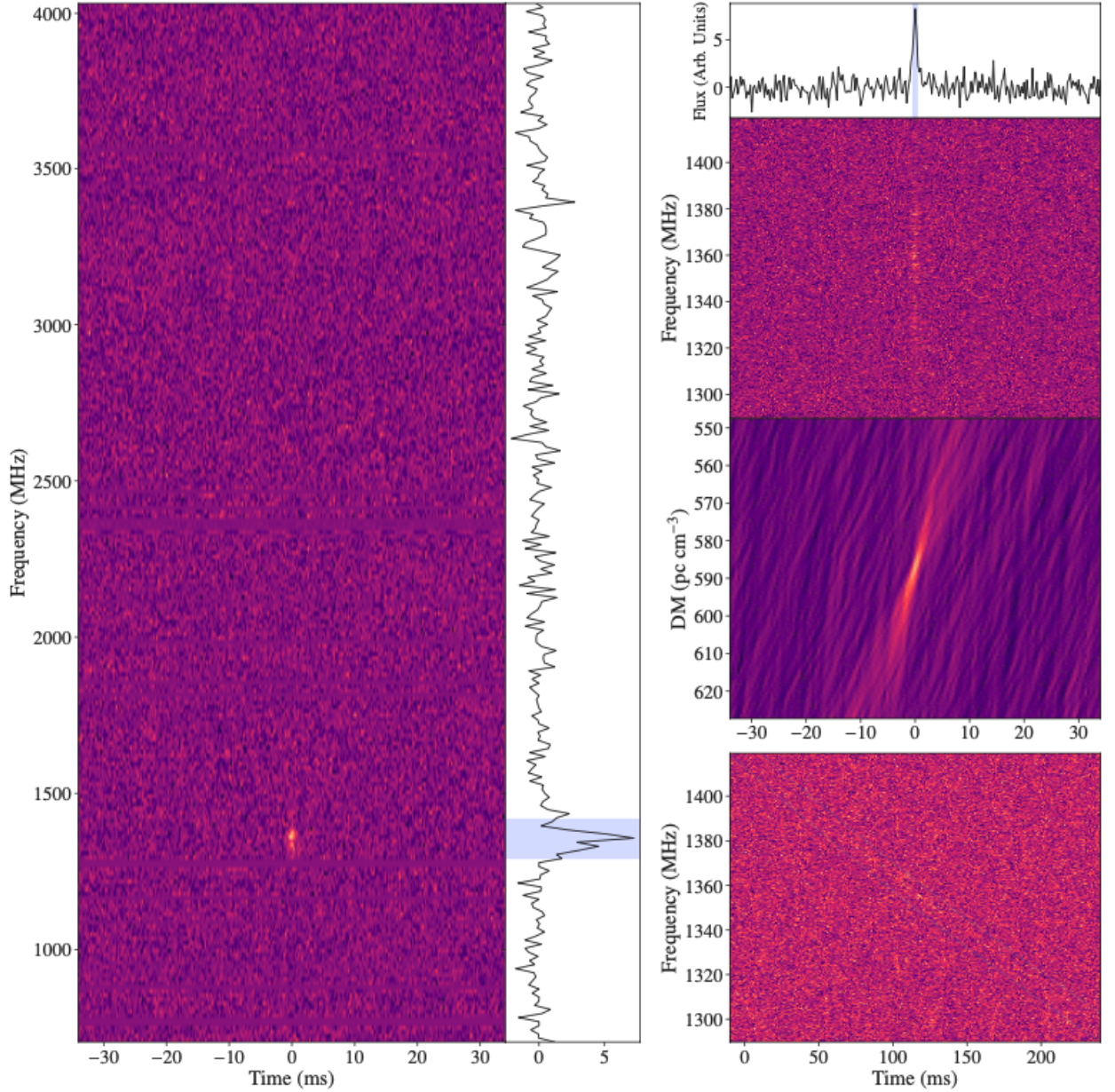


Figure 1.7: Example of a very narrow-band FRB: FRB 20190711A (image from Kumar et al., 2021a). Left subplot: the left-hand panel shows the dynamic spectrum and the right-hand panel shows the time-averaged on-pulse spectrum across the full UWL band. Right subplot: The top panel shows the dynamic spectrum of the sub-band of the UWL band where the burst occurred. Above and below this panel, there are the frequency-averaged flux density and the DM-time image (see Chap. 2), respectively. The bottom panel is the dynamic spectrum of the dispersed burst.

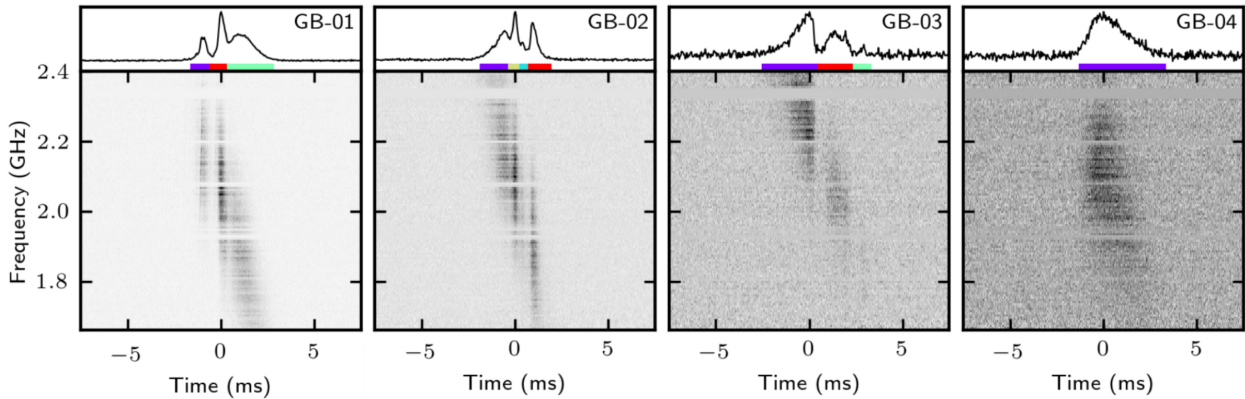


Figure 1.8: An example of four bursts, all seen from FRB 20121102A, which show multi-component and/or downward frequency drift (image adapted from Hessels et al., 2019).

The first rFRB to show such peculiar property was, as teased in Sec. 1.1.1, FRB 20180916B. The periodicity was announced by the CHIME/FRB collaboration (see e.g. Fig. 1.9 a, Chime/FRB Collaboration et al., 2020), thereafter opening a new opportunity window to study the FRBs.

Indeed, after their findings of $P_a \sim 16.3$ days and $W_a \sim 5.4$ days, a plethora of observations followed, thanks also to the prompt localisation of the FRB (Marcote et al., 2020; Tendulkar et al., 2021) in the outskirts of a spiral galaxy at a luminosity distance of only 149 Mpc.

In contrast with the case of FRB 20121102A, FRB 20180916B does not have an associated PRS. Like FRB 20121101A, also FRB 20180916B is a quite active source; however FRB 20180916B tends to favour lower emission frequencies (Pastor-Marazuela et al., 2021; Pleunis et al., 2021; Chawla et al., 2020; Pilia et al., 2020) in the hundreds of MHz range, rather than the GHz frequencies (Bethapudi et al., 2022; Pastor-Marazuela et al., 2021; Aggarwal et al., 2020) which are a usual feature of FRB 20121102A. Polarimetric measurements showed that FRB 20180916B has an $|RM| \sim 10^2 \text{ rad m}^{-2}$, but it is also showing a peculiar secular linear increase of the $|RM|$ (Mckinven et al., 2022), occurred in the timescale of about a year (beginning of 2021- beginning of 2022). At the time of writing of this manuscript there are yet no reports about updated RM measurements. Therefore we cannot state whether this linear increase is keep going until now, or the trend is changing.

A few months after the assessment of FRB 20180916B being a pFRB, also FRB 20121102A showed to be periodic and thus became the second pFRB (see e.g. Fig. 1.9 b, Rajwade et al., 2020; Cruces et al., 2021). Its activity period is $P_a \sim 161$ days, while the duration of the window is $W_a \sim 90$ days.

This periodic activity property has not been found yet in any of the rest of the 23 rFRBs, not even in remarkably highly-active sources as FRB 20200120E or FRB 20201124A (Lanman et al., 2022).

The fact that some rFRB are periodically active has a high impact in this field of research. From a theoretical point of view, the models must take into account this periodicity, but also for an experimental aspect, that allows one to schedule more easily multi-instruments campaigns, such as multi-wavelength campaigns, as we will discuss in Chap. 4. It is impossible not to notice the order of magnitude difference between the two activity periods. What causes this difference? Is it an orbital period or something different? Due to this large difference in the periodic activity perhaps all the rFRBs are periodically active but the period time scale is far greater than the one of FRB 20121102A, maybe larger than a

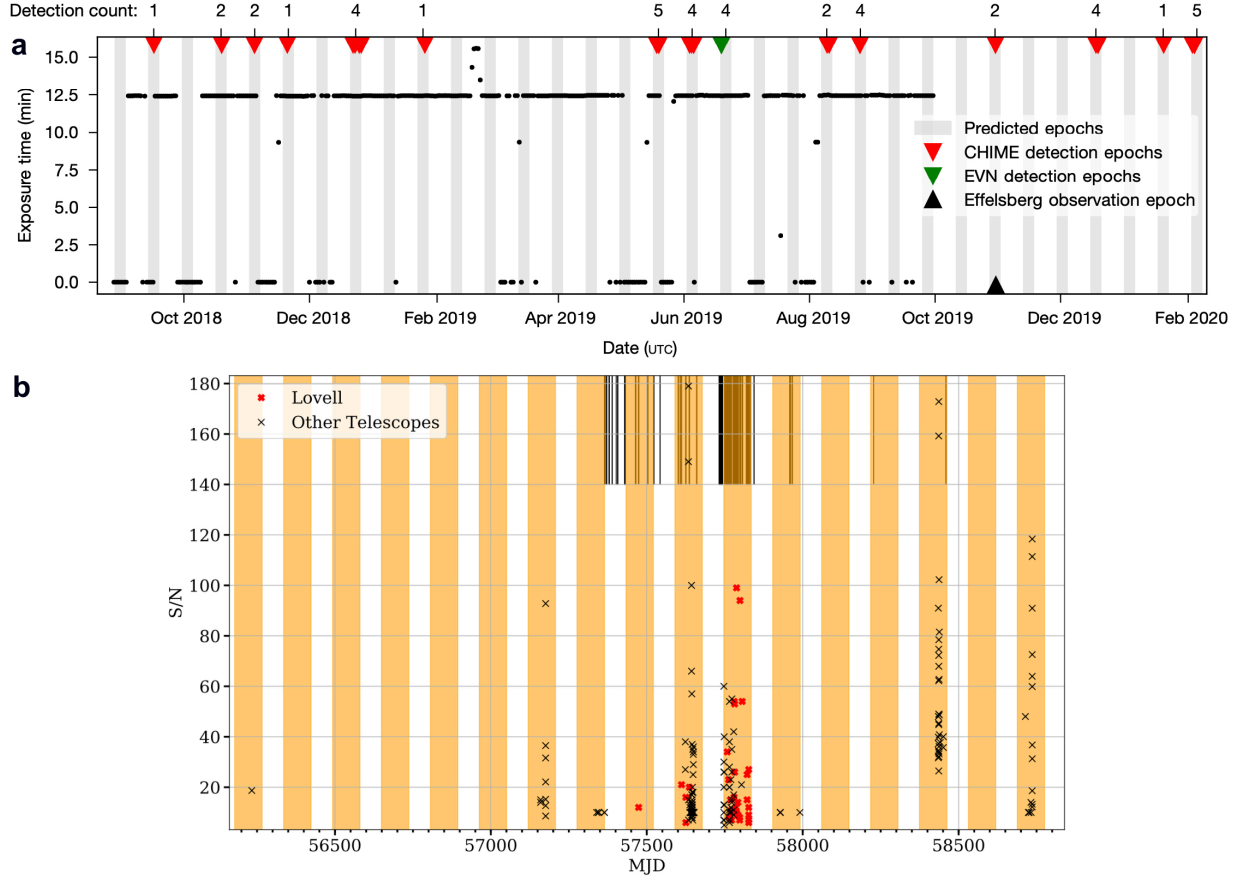


Figure 1.9: Time of arrivals of the bursts detected for FRB 20180916B (a) and FRB 20121102A (b). In both cases the bursts fall in activity windows of ~ 5 days periodically spanned in ~ 16 days for FRB 20180916B and ~ 90 days spanned in ~ 160 days for FRB 20121102A. Image adapted from Chime/FRB Collaboration et al. (2020) for FRB 20180916B and from Rajwade et al. (2020) for FRB 20121102A.

human lifespan. Having the possibility to study only two pFRBs makes it quite challenging to answer these (and many other) questions.

We conclude this section reporting two last additional cases of periodicity, however in a completely different time-scale, thus not making them to nominally belong to the class of the pFRBs. A one-off FRB detected by CHIME, FRB 20191221A (see Fig. 1.10), showed a long (roughly 3 s) burst, split into many components, with a periodic separation of about 217 ms (at a 6.5σ significance), making it an outlier in the FRB population. Pastor-Marazuela et al. (2022) recently found another one-off FRB (FRB 20201020A), similar to FRB 20191221A. However the authors also cautiously remark that the hints of a sub-second periodicity in the burst of FRB 20201020A is not as much significant (2.5σ) as opposed to the periodicity observed in the aforementioned FRB 20191221A.

1.2.13 Chromatic Activity of pFRBs

In order to describe the behaviour of FRB 20180916B and FRB 20121102A (both periodically active), we need to introduce an additional parameter, namely the phase ϕ of the cycle of activity. Considering the time of arrival (TOA) of a burst from a pFRB, the activity phase

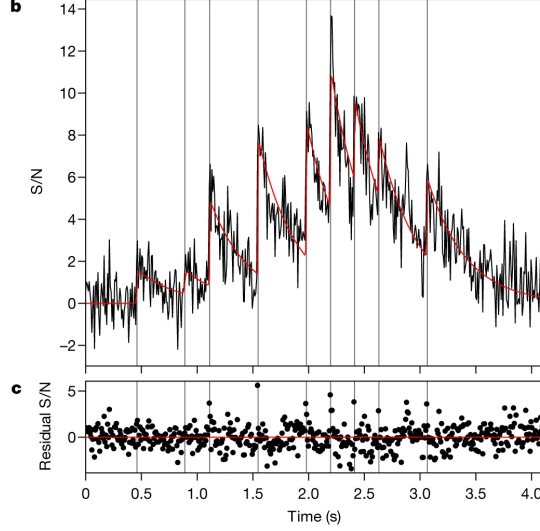


Figure 1.10: Time series (top) and fit residuals (bottom) of FRB 20191221A. This FRB shows a multi-component structure, where each component is periodically separated of about 217 ms (image adapted from Chime/FRB Collaboration et al., 2022)

ϕ can be simply computed by folding the TOA with respect to the activity period P_a as:

$$\phi = \frac{\text{TOA} - T_0}{N_{\text{fold}} P_a}, \quad (1.22)$$

where T_0 is a reference epoch and N_{fold} is the integer number of cycles from the reference epoch to the TOA. Of course N_{fold} can be written as:

$$N_{\text{fold}} = \left\lfloor \frac{\text{TOA} - T_0}{P_a} \right\rfloor, \quad (1.23)$$

where, with square brackets $\lfloor \cdot \rfloor$, we mean the integer part function. We emphasize that, contrary to pulsars and RRATs, where ϕ is related to the rotational period of the underlying NS, in the case of a pFRB ϕ is related to its activity cycle. It is useful to introduce the phase ϕ since it may allow us to reveal underlying patterns for some FRB key parameters.

For instance, the many detections of FRB 20180916B at different radio frequencies, from ~ 150 MHz (Pleunis et al., 2021; Pastor-Marazuela et al., 2021) up to 6 GHz (Bethapudi et al., 2022), have led to show that the FRB 20180916B activity seems to follow a chromatic pattern: that is there is a dependence between the activity phase ϕ and the central frequency of the band at which a given burst has been observed ν_A , as showed by Pastor-Marazuela et al. (2021) and confirmed by Pleunis et al. (2021). In fact, the occurrence of bursts at higher and lower frequencies than the CHIME band only partially overlap with the CHIME-derived active phase window of FRB 20180916B: the bursts detected at L-band (around 1.4 GHz), as for example the ones detected by Apertif (Pastor-Marazuela et al., 2021), have an occurrence distribution shifted ~ 0.7 days earlier (hence at an earlier ϕ) than the CHIME-detected distribution. In contrast, bursts detected at the lower LOFAR frequencies show a phase shift of ~ 3 days (i.e. at later activity phases ϕ , Pleunis et al., 2021).

The differences in the active window seem to include not only a different onset (and, likely, end-) time, but also its duration: the higher frequencies active phases appear to be shorter than the lower frequency ones (Bethapudi et al., 2022; Pastor-Marazuela et al., 2021). In parallel, the average width of the bursts becomes larger at lower frequencies

(Pastor-Marazuela et al., 2021). However, this is partially due to scattering, and its effect is in general limited to only the lowest frequencies for this FRB (Pastor-Marazuela et al., 2021; Marcote et al., 2020; Pilia et al., 2020).

This trend somehow resembles the radius-to-frequency mapping (RFM) behaviour observed in several pulsars, which links emission at different heights in the pulsar magnetosphere to different observed radio frequencies (see eg. the article series from Rankin, 1983a; Rankin, 1983b; Rankin, 1986; Rankin, 1990; Radhakrishnan and Rankin, 1990; Rankin, 1993; Mitra and Rankin, 2002; Rankin and Ramachandran, 2003), as discussed by Pleunis et al. (2021).

1.3 The Zoo of Models

Before CHIME started to operate in the 2018, for about a decade the number of models proposed to explain the nature of the FRBs was greater than the sample of observed bursts. Describe and discuss all of them in depth is out of this Thesis purpose and we will leave the readers to Zhang (2022), Zhang (2020), and Platts et al. (2019) for comprehensive reviews. In the following two sub-sections, we will first report on very general observational constraints to the models, and then we will review the main classes of proposed emission mechanisms.

1.3.1 Observational Constraints

The long series of observational facts, although they are not yet sufficient to point to a single (unified) model, can already lead to set some constraints.

As mentioned in Sec. 1.2.5, the ms-duration of the FRBs already put a huge constraint on the plausible objects behind FRBs, pointing towards compact objects as NSs and stellar BHs.

The fact that some FRBs are repeaters severely rules out all the cataclysmic scenarios for these kind of sources. For instance, the merging of NSs (Hansen and Lyutikov, 2001), or the collapse of supra-massive NSs (Falcke and Rezzolla, 2014), can be invoked only as a possible explanation for the one-off FRBs. In this context, one may wonder whether the one-off FRBs are really bursts *una tantum*: at a very formal level, it is impossible to exclude the possibility that the FRBs classified so far as one-off events are in reality rFRBs which simply were “not enough observed” or with long quiescent time. Indeed, whenever trying to catalogue an FRB as a one-off event, it is very difficult to quantify the role of the instrumental sensitivity and of the observing time dedicated to the given source.

Furthermore, the two discovered pFRBs adds an additional parameter to the modelling. In order to explain the periodic activity of FRB 20121102A and FRB 20180916B, various options have been postulated. From a binary motion in a two body system (see e.g. Deng, Zhong, and Dai, 2021; Lyutikov, Barkov, and Giannios, 2020; Ioka and Zhang, 2020) to rotation (Beniamini et al., 2022; Beniamini, Wadiasingh, and Metzger, 2020) or precessional effects (Tong, Wang, and Wang, 2020; Yang and Zou, 2020; Zanazzi and Lai, 2020), in the case of a single object.

The fact of having detected FRBs only external to our Galaxy, apart from the radio bursts from the SGR J9135+2154 as we will discuss in Chap. 4, shows that an FRB event should be rather rare to happen in a given Galaxy and only when considering all the galaxies in the Universe it becomes as frequent as required by the observational constraints. In fact, the observed FRB event all-sky rate is about $\mathcal{O}(10^3)$ days⁻¹ above a fluence threshold of 1 Jy ms (Petroff, Hessels, and Lorimer, 2019), which translates into a volumetric rate

of $\mathcal{O}(10^4) \text{ year}^{-1} \text{ Gpc}^{-3}$. This is higher than the rates of all the so far known candidate cataclysmic progenitor events and also higher than the birth rates of candidate compact-object sources (Ravi, 2019).

As to the energy considerations, for sure, from the high brightness temperatures, as we already discussed, the emission mechanism must be coherent, and, whichever the source engine behind the FRB emission is, that should be capable to reach the luminosities and energetics that we mentioned in Sec. 1.2.7. It is interesting to mention that the majority of the X-ray bursts from SGR J1935+2154 were not associated with any radio burst (Lin et al., 2020): this may mean that the luminosity/energy of the radio bursts could be released in a beamed way (at least for the FRBs produced by magnetars alike SGR J1935+2154).

In Sec. 1.4 we will discuss additional constraints, related to the chromatic burst emission distribution of FRB 20180916B.

1.3.2 Classification by Radiation Mechanism

Following the discussion in Zhang (2020), and the requirement of a coherent emission, the current models can be broadly grouped into two categories: models which exploit the magnetosphere of a rotating compact object (we will call them “*pulsar-like*” models) or models invoking relativistic shocks outside the magnetosphere (we will call them “*GRB-like*” models).

Pulsar-like Models. These kinds of models explain the coherent emission via the production of electron-positron pairs with number density proportional to the Goldreich-Julian density (Goldreich and Julian, 1969):

$$n_{\text{GJ}} = -\frac{1}{2\pi c e} \boldsymbol{\Omega} \cdot \mathbf{B} , \quad (1.24)$$

where $\boldsymbol{\Omega}$ is the angular velocity vector of the rotating compact object and $\mathbf{B}$ is its magnetic field vector. For instance, Lyubarsky (2020) proposed that a magnetic burst is initially made within the inner magnetosphere of a magnetar and when it propagates in its far-regions triggers magnetic reconnections capable to produce magnetosonic waves which leave the magnetosphere. Lu, Kumar, and Zhang (2020a), Yang et al. (2020), Lu and Kumar (2018), Yang and Zhang (2018), Kumar, Lu, and Bhattacharya (2017), and Katz (2014) instead exploit curvature radiation by clusters of charged particles (see e.g. Fig. 1.11 a).

GRB-like Models. As the name suggests these models try to use the lesson learnt from GRB models, which invoke synchrotron maser shocks (Sagiv and Waxman, 2002). The common ground of these models is based on the formation of shock(s) and the interactions among them and with the ambient medium. In particular, the central engine produces an ultra-relativistic outflow which collides with a stationary medium creating a shock (see Fig. 1.11 b from Metzger, Margalit, and Sironi, 2019). The FRB duration Δt in this framework is related to the radius where the shock occurred R_{shock} as

$$\Delta t \sim \frac{R_{\text{shock}}}{c\gamma^2} , \quad (1.25)$$

where γ is the Lorentz factor of the outflow. Typical shock radii are of the order of 10^{12} cm , implying an outflow with $\gamma > 100$ in order to have ms-duration FRBs. The physical size l of the source engine will be then

$$l \sim \frac{R_{\text{shock}}}{\gamma^2} , \quad (1.26)$$

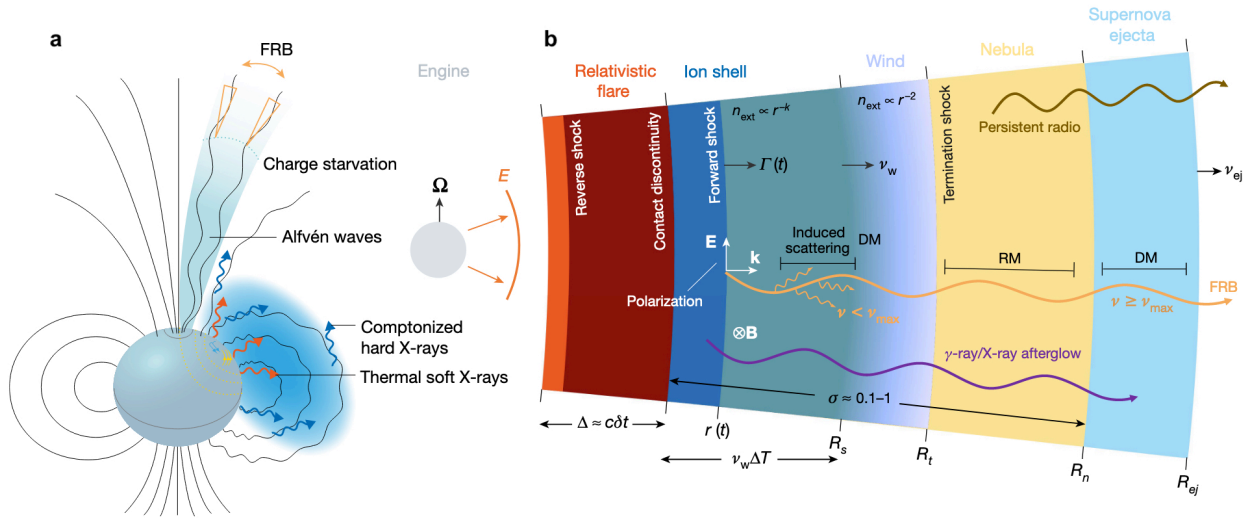


Figure 1.11: An example of a pulsar-like model (a, image adapted from Lu, Kumar, and Zhang, 2020a) and an example of a GRB-like model (b, image adapted from Metzger, Margalit, and Sironi, 2019).

requiring hence a compact object. A list of several variations of these kind of models can be found in: Beloborodov (2020), Plotnikov and Sironi (2019), Beloborodov (2017a), Ghisellini (2017), Waxman (2017), and Lyubarsky (2014).

A Common Engine. Regardless the coherent emission comes from a magnetosphere or from shocks, the current observational data seem indicating that the FRB source engine has to be, again, a compact object with a strong magnetic field.

This consideration, remarkably strengthened by the analysis of the SGR J1935+2154 event, led to invoke the magnetars as the favourite generators of FRBs. Magnetars⁵ are class of NSs with magnetic fields of the order of 10^{14} G (Kaspi and Beloborodov, 2017), roughly $10^2 - 10^3$ more intense than the typical magnetic field of a pulsar. Historically, magnetars have been detected in the form of Soft Gamma-Ray Repeaters (SGRs) or as Anomalous X-ray pulsars (AXPs). The strong magnetic field is the dominant source of their emission, contrary to the case of the pulsars which are powered by their rotation. After the discovery of the LB, SGR giant flares were proposed to explain it (Popov and Postnov, 2010). The enviroment of FRB 20121102A (Michilli et al., 2018) raised the hypothesis that young magnetars born in long GRBs and superluminous supernovæ are the sources behind of rFRBs (Beloborodov, 2017a; Metzger, Berger, and Margalit, 2017), although a unambiguous association between an FRB and a GRB has not yet found (Curtin et al., 2022; Men et al., 2019). Further localisation of other rFRBs showed that the host of FRB 20121102A could be an atypical host (Marcote et al., 2020; Bannister et al., 2019), weakening this idea of the rFRBs born from long GRBs (Li and Zhang, 2020). However the SGR J1935+2154 event unmistakably establishes a connection between magnetars and FRBs: some of them have to be made by magnetars.

⁵See the website <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html> for the list of magnetars currently discovered in our Galaxy.

1.4 Absence of Chromatic Activity from FRB 20121102A (Original Contribution)

In this section, by collecting the whole dataset of the published bursts from FRB 20121102A and from FRB 20180916B (reported in Tab. 1.1), we show that (i) FRB 20121102A does not possess any chromatism in the distribution of the windows of activity along its periodic cycle. This is in striking contrast to the case of the FRB 20180916B. Furthermore, we will show that, interestingly, (ii) the dependence of the central frequency of the burst ν_A as function of the activity phase ϕ for the FRB 20180916B can be well described by an exponential decay.

1.4.1 Chromaticity Plot

As a preliminary step we computed the activity phase as described by Eq. 1.22, from the bursts TOA collected for both sources. Then the activity phases have been obtained by folding the bursts TOA with respect to an activity period of $P_a = 161$ days and a starting epoch $T_0 = 57057$ MJD (Cruces et al., 2021) for FRB 20121102A and $P_a = 16.33$ and $T_0 = 58369.40$ MJD (Pleunis et al., 2021) for FRB 20180916B.

For each FRB source we will have then, for each telescope T , a set of points $(\phi^i, \nu_A^i, \Delta\nu^i)^{(T)}$, with $i = 1, \dots, N_b^{(T)}$, where $N_b^{(T)}$ is the number of bursts detected by the telescope T . The set of points represents the phase, central frequency and frequency width of the i -th burst of the T -th telescope.

For each telescope we can then assign a telescope-centroid point $(\phi, \nu_A)^{(T)}$ computed by taking the average phase and burst central frequency:

$$\phi^{(T)} = \frac{1}{N_b^{(T)}} \sum_{i=1}^{N_b^{(T)}} \phi^{i(T)} , \quad (1.27)$$

$$\nu_A^{(T)} = \frac{1}{N_b^{(T)}} \sum_{i=1}^{N_b^{(T)}} \nu_A^{i(T)} . \quad (1.28)$$

We then assign, to each telescope burst-averaged phase $\phi^{(T)}$, its standard deviation $\sigma_{\phi^{(T)}}$. For each telescope burst-averaged central frequency ν_A , rather than its standard deviation, we assign its burst-averaged frequency width:

$$\Delta\nu^{(T)} = \frac{1}{N_b^{(T)}} \sum_{i=1}^{N_b^{(T)}} \Delta\nu^{i(T)} , \quad (1.29)$$

as the standard deviation of the burst central frequency would be sub-optimal for telescopes with very limited observational bands, since ν_A will mostly coincides with the telescope central frequency.

1.4.2 Results

Figure 1.12 depicts, in linear-log scale, the telescope burst-averaged central frequency ν_A as a function of the telescope burst-averaged phase ϕ , both for FRB 20121102A (detected by 14 telescopes) and for FRB 20180916B (detected by 13 telescopes).

From the figure we see that the points are quite randomly scattered in the case of the FRB 20121102A, whereas for the FRB 20180916B we clearly see a linear decreasing trend.

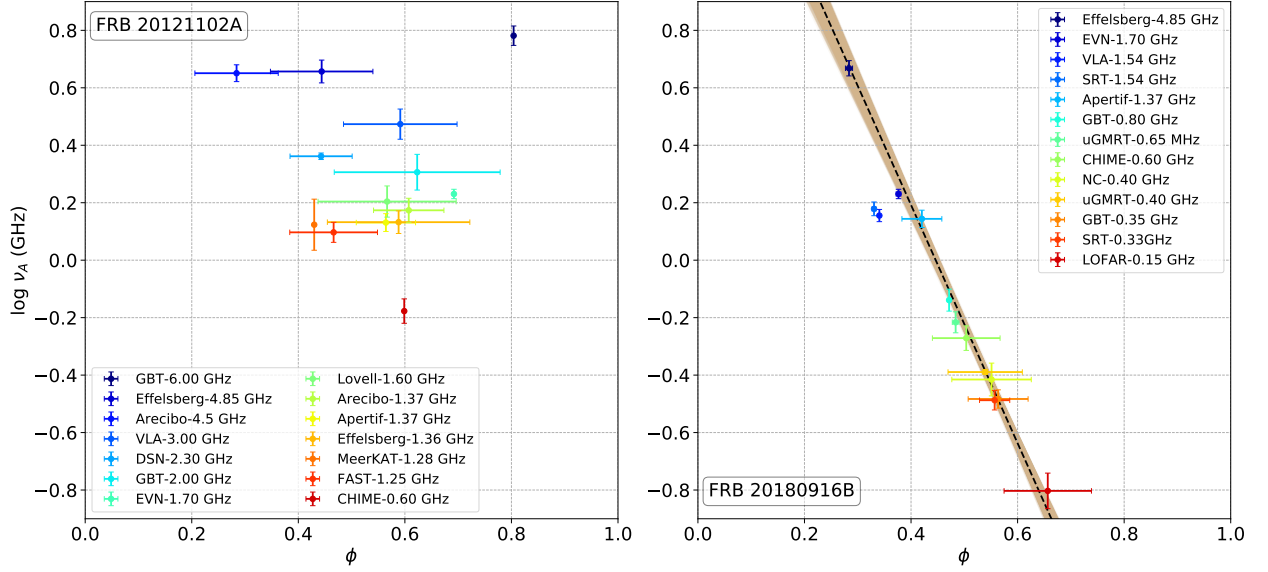


Figure 1.12: Logarithm of the burst-averaged central frequency ν_A as function of the burst-averaged phase ϕ of the periodicity cycle for FRB 20121102A (left panel) and FRB 20180916B (right panel). In the right panel the black dashed line depicts the best-fit line and the brown region consists of all the realisations of the fit drawn by the posterior distributions. The data points EVN-1.7 GHz, VLA-1.54 GHz, SRT-1.54 GHz (SRT-L), GBT-0.80 GHz and uGMRT-0.65 GHz have been not used for the fit (see Sec. 1.4.2 for further details).

Due to the small sample of bursts available at the time of their publications, neither Pastor-Marazuela et al. (2021) nor Pleunis et al. (2021) did try to quantitatively evaluate this chromatic trend. We try to model this behaviour with an exponential decay function as:

$$\nu_A = \nu_C e^{-\frac{\phi}{\phi_C}}, \quad (1.30)$$

which, taking the logarithm (base 10) on both sides means:

$$\log \nu_A = \log \nu_C - \frac{\phi}{\phi_C} \log e, \quad (1.31)$$

where ϕ_C and ν_C are a characteristic phase and a characteristic frequency for $\phi = 0$ respectively. We fitted the data showed in Fig. 1.12 with a straight line, described by Eq. 1.31, where $\log \nu_C$ and ϕ_C are the fit free parameters.

Out of the 13 points available, we did not include in the fits the following events: the EVN-1.7 GHz, VLA-1.54 GHz, SRT-1.54 GHz (SRT-L), GBT-0.80 GHz and uGMRT-0.65 GHz. This choice comes from the fact that all these events happened within a single day or, like in the case of the VLA, only a single event is available. Because of the ~ 16 days periodic activity of FRB 20180916B, folding the bursts TOA at such large period even in the case of bursts happening a few hours apart each other cannot give significantly different values of ϕ within the error for the activity period. Because of this we chose only the telescopes for which bursts have been detected on different days.

We initially performed a frequentist fit by using an Orthogonal Distance Regression (ODR), exploiting the `scipy.odr` package. We obtained, as best-fit parameters, $\phi_C = 0.104 \pm 0.003$, $\nu_C = 69 \pm 2$ GHz ($\chi^2/\text{d.o.f.} = 5.4/6$). We then performed a Bayesian fit, via a Nested Sampling analysis to get more robust error estimations. We exploited the software package BILBY (Ashton et al., 2022; Ashton and Talbot, 2021; Ashton et al., 2019). We used

uniform distributions $\phi_C \in \mathcal{U}(0, 1)$ and $\log \nu_C \in \mathcal{U}(-2, 2)$ (with ν_C in GHz) as priors. Figure 1.13 shows the posterior distributions, which report, as best parameters, $\phi_C = 0.105 \pm 0.003$, $\log \nu_C = 1.85 \pm 0.05$ (hence $\nu_C = 71 \pm 5$ GHz). These results are compatible with the frequentist fit. The model remarkably agree with the data however Eq. 1.30 would imply emission at $\nu_A = 71$ GHz for $\phi = 0$ and, on the same time for $\phi = 1$, at 5 MHz. We point out that this is a preliminary analysis and it is necessary to further refine Eq. 1.30 for such extreme phases.

1.4.3 Discussion and Conclusions

As opposed to FRB 20180916B, we mentioned that FRB 20121102A does not show a trend and therefore it seems that the two sources behave differently. However, there are some important considerations to make. On one hand, the low-frequency (P-band) space for FRB 20121102A has been explored only by CHIME/FRB, with one single detection (Joseph et al., 2019). On the other hand, there is an outlier point at high-frequency (~ 6 GHz) and late-phase (~ 0.8) which results from the sample of bursts detected by Gajjar et al. (2018) and Zhang et al. (2018). These detections happened on the same day and so they do not result from a satisfactorily averaged sample of bursts at this frequency: further observations are needed. Because of these two outliers, it is not possible to completely discard the chromaticity scenario also for FRB 20121102A even though, with the current sample of bursts, we find it unlikely.

The absence of chromatic activity in FRB 20121102A contrary to FRB 20180916B establishes a remarkable difference between the two sources. Li and Zanazzi (2021) for instance proposed that either a long period magnetar (Beniamini, Wadiasingh, and Metzger, 2020) or a slowly free precessing magnetar (Zanazzi and Lai, 2020) could explain both the periodic and the frequency dependent activity of a source like FRB 20180916B. In fact, both models are able to predict that the high frequency bursts statistically arrive at earlier phases and the low frequency ones at later phases. However in the free-precession model the source tends to be more active at lower frequencies, whereas in the case of the slowly rotating magnetar there is no favourite frequency channel for the burst production.

The first scenario seems to better fit the observed properties of FRB 20180916B since its activity window appears wider at lower frequency (Pastor-Marazuela et al., 2021). This fact, in particular, also disfavors orbital models such as binary wind models (Ioka and Zhang, 2020; Lyutikov, Barkov, and Giannios, 2020) as discussed by Pastor-Marazuela et al. (2021). In fact in such models, the free-free absorption in the wind from the companion star, conceals the coherent radio emission of the putative FRB source in a way as the opposite as observed. The wind from the companion makes the system optically thicker and the optical depth (in such models) decreases at higher frequencies and increases at lower frequencies, which is in contrast with what we see for FRB 20180916B. The bursts at higher frequencies should have higher chances to escape the companion comb and they should come in broader phase activity windows (that is larger standard deviations in Fig. 1.12) and on the other hand bursts at lower frequencies should behave in a opposite manner.

Conversely, regarding FRB 20121102A, the absence of chromaticity combined with the evidence of DM and RM variations (Hilmarsson et al., 2021; Michilli et al., 2018), which are an additional prediction from these binary wind models (Ioka and Zhang, 2020; Lyutikov, Barkov, and Giannios, 2020), and furthermore with its extremely long period of activity of ~ 160 days could be rather explained by orbital motion models (Wada, Ioka, and Zhang, 2021).

None of the aforementioned models prescribes a detailed relation among the phase of the

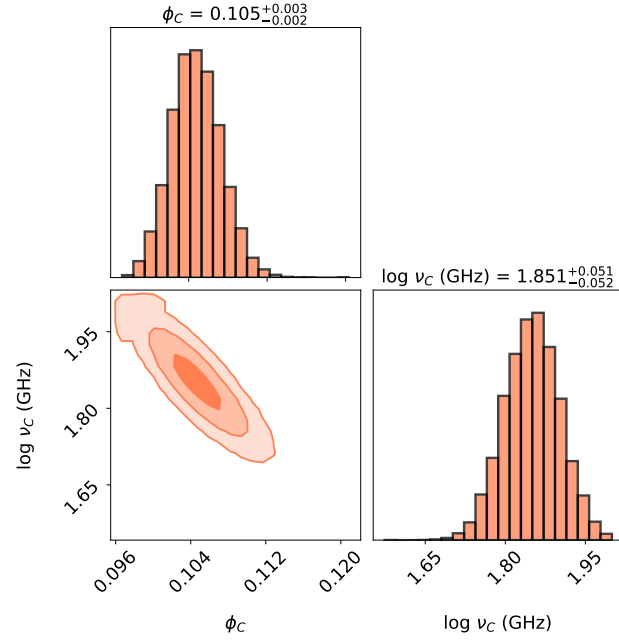


Figure 1.13: Posterior distributions of the linear fit from Eq. 1.31.

window of activity and the frequency of observation in that window. Our empirical relation, like the one recently proposed also by Bethapudi et al. (2022), in which they similarly modelled the chromaticity by using a power-law, set strong requirements, which all the current or future models will need to address.

Table 1.1: Dataset considered for FRB 20121102A and FRB 20180916B.

Telescope-Receiver	Reference
FRB 20121102A	
GBT-6 GHz	Zhang et al. (2018) and Gajjar et al. (2018)
Effelsberg-4.85 GHz	Hilmarsson et al. (2021) and Spitler et al. (2018)
Arecibo-4.5 GHz	Hilmarsson et al. (2021) and Michilli et al. (2018)
VLA-3 GHz	Hilmarsson et al. (2021), Law et al. (2017), and Chatterjee et al. (2017)
DSN-2.3 GHz	Pearlman et al. (2020) and Majid et al. (2020)
GBT-2 GHz	Hessels et al. (2019), Scholz et al. (2017), and Scholz et al. (2016)
EVN-1.7 GHz	Marcote et al. (2017)
Lovell-1.6 GHz	Rajwade et al. (2020)
Arecibo-1.37 GHz	Jahns et al. (2022), Hewitt et al. (2021), and Aggarwal et al. (2021); Hessels et al. (2019), Gourdji et al. (2019), and Scholz et al. (2017); Spitler et al. (2016) and Spitler et al. (2014)
Apertif-1.37 GHz	Oostrum et al. (2020)
Effelsberg-1.36 GHz	Cruces et al. (2021), Houben et al. (2019), and Hardy et al. (2017)
MeerKAT-1.28 GHz	Caleb et al. (2020)
FAST-1.25 GHz	Li et al. (2021)
CHIME-0.6 GHz	Joseph et al. (2019)
FRB 20180916B	
Effelsberg-4.85 GHz	Bethapudi et al. (2022)
EVN-1.7 GHz	Marcote et al. (2020)
VLA-1.54 GHz	Aggarwal et al. (2020)
SRT-1.54 GHz	Anedda (2022)
Apertif-1.37 GHz	Pastor-Marazuela et al. (2021)
GBT-0.80 GHz	Sand et al. (2022)
uGMRT-0.65 GHz	Marthi et al. (2020)
CHIME-0.60 GHz	Mckinven et al. (2022) and Pleunis et al. (2021); Chime/FRB Collaboration et al. (2020); CHIME/FRB Collaboration et al. (2019b)
NC-0.40 GHz	Trudu et al. (2022) (see Chap. 3 of this thesis)
uGMRT-0.40 GHz	Sand et al. (2022) and Pleunis et al. (2021); Trudu et al. submitted (see Chap. 4 of this thesis)
GBT-0.35 GHz	Chawla et al. (2020)
SRT-0.33 GHz	Pilia et al. (2020); Trudu et al. under review (see Chap. 4 of this thesis)
LOFAR-0.15 GHz	Pastor-Marazuela et al. (2021) and Pleunis et al. (2021)

FRB Data Recording and Processing

In this chapter we will first introduce, how the radio astronomical data are recorded and processed for FRB science. In the second section we will discuss the current state of the art of FRB searches and classification. In the third section we will introduce the High Time Resolution Universe (HTRU) survey. At last (Sec. 2.4 onwards) we will report on an original contribution: the search for narrow-band FRBs in the HTRU survey. First we will show how much signal-to-noise ratio can be gained searching for FRBs in sub-banded regions of the original data, and secondly, as a preliminary result, we present the detection of 18 new bursts from this survey.

This chapter contains the the results of the following work:

- **M. Trudu** et al., “*The search for narrow-band FRBs in the High Time Resolution Universe Survey Southern Hemisphere*”, in preparation.

2.1 Data Acquisition

The FRB data acquisition, due to the similarities with the pulsars we described in Chap. 1, follows the same well established procedures developed throughout the years by pulsar astronomers and engineers since the discovery of the first pulsar. In this section we briefly describe how pulsar/FRB data are acquired and we will leave the readers to Lorimer and Kramer, 2005, Chap. 5 and Ridolfi, 2017, Chap. 2 for a comprehensive introduction.

As a start, in order to process the EM radiation coming from a celestial source and make it processable, a modern radio telescope follows, three main steps: the radiation is firstly collected, then frequency down-converted and lastly sampled and digitised.

Signal Collection. The radiation coming from a source received by the telescope is firstly collected by a mirror, then a *receiver* (or *feed*), gathers the EM field (one or both the polarisations of the field according to the design of the instrument) through a wave guide. The receiver, in general, operates over a frequency range, dictated by the scientific goals of the instrument and the technological limitations due to the electronics. The radiation is then converted into voltages, amplified by a Low-Noise Amplifier and then convolved with

a low-pass filter.

Down-conversion. In order to be correctly processed without loss of information or power, the signal is usually brought at lower frequencies via a Local-Oscillator (LO), which produces a monochromatic signal of a fixed frequency. The signal is combined with this monochromatic sinewave, and the result is an intermediate signal of frequencies the sum and difference of the original signal and the frequency of the LO. Subsequently, through another filter, only the component at lower frequency is kept and eventually, as a last step, the frequency lowered signal is additionally amplified.

Digitisation. The signal, after being collected and down-converted is then sampled and digitised in the *backend* by an Analogue-to-Digital Converter (ADC) in the best cases at the Nyquist rate (Nyquist, 1928), that is twice the signal bandwidth, in order to preserve all the initial information.

2.1.1 Pre-Processing

The signal can be then further processed to meet the scientific needs of a specific experiment. In the case of the monitoring of rFRBs, when their DM is known, the dispersion delay effect discussed in Chap. 1 affecting the signal can be corrected via a technique called **coherent dedispersion**. It can be proved (Hankins, 1971; Hankins and Rickett, 1975) that the DM delay of a signal $f(t)$ can be completely removed by multiplying it in the Fourier domain with a transfer function

$$H(\nu + \nu_c) = e^{i2\pi\mathcal{D}\text{DM}\frac{\nu^2}{(\nu+\nu_c)\nu_c^2}}, \quad (2.1)$$

where ν_c is the central frequency of the signal (which could be different from the initial one due to the down-conversion procedure discussed earlier) and $\mathcal{D}$ is the DM delay constant we introduced in Sec. 1.2.1, and then the corrected signal $f_{\text{corr}}(t)$ can be retrieved by doing an inverse Fourier transform:

$$f_{\text{corr}}(t) = \mathcal{FT}^{-1} \left[\tilde{f}(\nu) H(\nu + \nu_c) \right], \quad (2.2)$$

where with $\mathcal{FT}$ we mean the Fourier Transform operator and $\tilde{f}(\nu)$ is the Fourier Transform of $f(t)$.

However in most cases the DM of the source is unknown and this requires to apply the coherent dedispersion for different DM trials. This case is computationally challenging even for modern acquisition systems. In fact, in order to apply the coherent dedispersion, the data have to be saved in a format that currently weighs $\sim$ TB per hour of recording. For instance, a hour-long recording with bandwidth of 200 MHz sampled at the Nyquist rate with a 8-bit depth would produce a dataset of 1.4 TB. Furthermore many coherent dedispersion trials require a remarkable computation time.

An elegant (but compromising as we will see) way to overcome the aforementioned problems is by using a technique called **incoherent dedispersion**. To perform the incoherent dedispersion it is compulsory first to process the signal $f(t)$ by channelising it with a *Short Time Fourier Transform* (STFT, Oppenheim, 1999). The signal $f(t)$, after being digitised, is a N point vector f_n , $n = 0, 1, \dots, N-1$. The standard discrete Fourier Transform (DFT) of f_n consists of projecting the signal in the conjugated space of the frequencies, which yields the vector

$$\tilde{f}^\alpha = \sum_{n=0}^{N-1} \omega(N)^\alpha_n f^n, \quad (2.3)$$

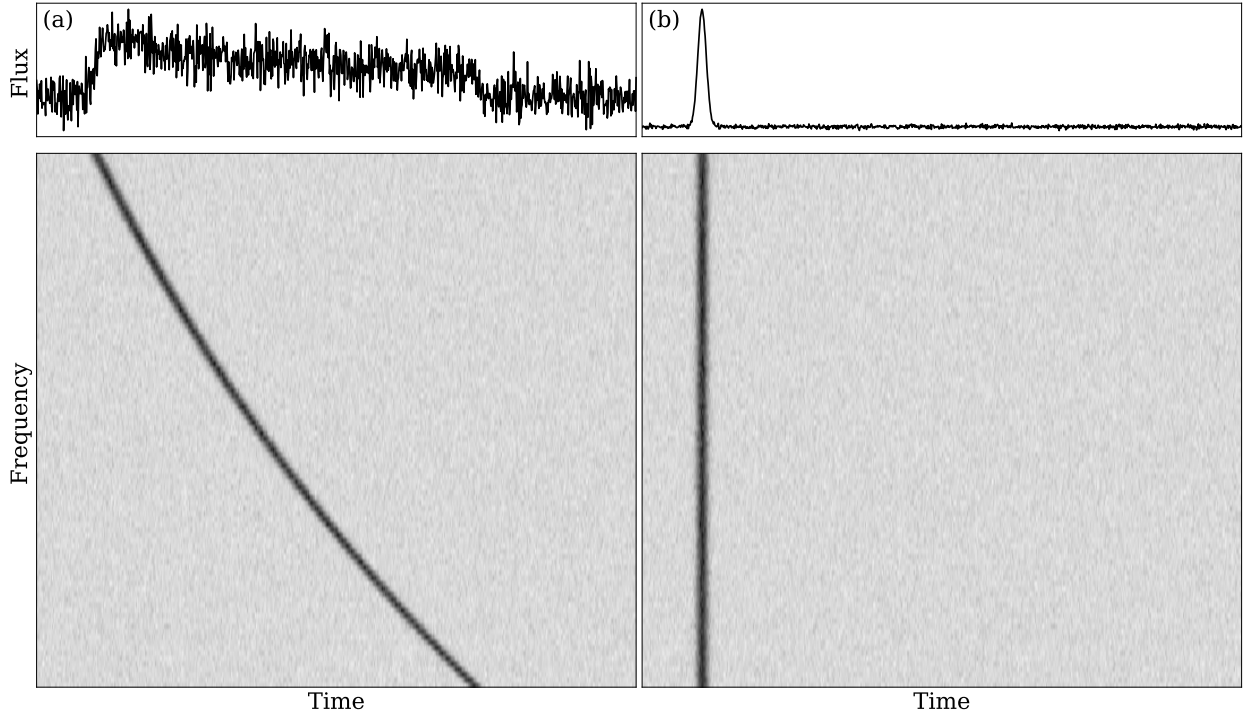


Figure 2.1: Frequency averaged time series (top) and dynamic spectrum (bottom) of a not DM corrected toy FRB (a) and after being DM corrected (b) via the incoherent dedispersion.

where the projectors are

$$\omega(N)_n^\alpha = e^{-i2\pi \frac{\alpha n}{N}}. \quad (2.4)$$

The DFT is an algorithm of complexity $\mathcal{O}(N^2)$ however with more optimised implementations, such the Fast Fourier Transform (FFT, Cooley and Tukey, 1965) a complexity of $\mathcal{O}(N \log_2 N)$ can be achieved. The STFT divides a signal into shorter vectors of equal length N_c and then performs, on each of these $N_s = \lfloor N/N_c \rfloor$ vectors, a FFT. The final product of the STFT is a complex matrix S_n^α of N_c frequency channels and N_s time bins, which “keeps” the original signal in both the frequency and time domain. If we have a single polarisation channel or if we are interested only on the intensity of the signal we can take the squared modulus:

$$F_n^\alpha = |S_n^\alpha|^2. \quad (2.5)$$

The matrix F_n^α is often times called *dynamic spectrum* or *spectrogram* of the signal. The pulsar/FRB data saved as matrix spectrograms are usually called *search mode* data (when searching for a pulsar or an FRB, only the total intensity matrix is sufficient). According to the time and frequency resolution one needs to achieve, the optimal number of channels N_c (and consequentially the number of time bins) is chosen. Furthermore, to meet disk space saving requirements the data are sometimes *decimated*, that is down-sampled in frequency, time or both. An example of search mode data are the SIGPROC filterbank (Lorimer, 2011) files.

After obtaining the search mode spectrogram F_n^α from the original time series $f(t)$, we can perform the incoherent dedispersion. The idea is simple: from Eq. 1.7 (see Sec. 1.2.1), we know the time delay experienced by each frequency channel of the signal. For each frequency channel we discretise in bins the respective DM delay and then shift each of row of the matrix F_n^α according to this delay in bins, as depicted in Fig. 2.1. The incoherent dedispersion algorithm has the advantage to be much faster than the coherent (see e.g.

Magro et al., 2011, for a fast implementation), which involves several FFTs of remarkably long vectors. However, as we stated initially it demands some compromises. When the matrix F_n^α is corrected for the DM delay via the incoherent dedispersion, each spectral channel, with resolution $d\nu$, will still retain its own DM smearing (intra-channel smearing). The intra-channel smearing δt_{DM} can be simply estimated by Taylor expansion of Eq. 1.7 at the first order:

$$\delta t_{\text{DM}} \simeq 8.3 \times 10^{-3} \left(\frac{\text{DM}}{\text{pc cm}^{-3}} \right) \left(\frac{d\nu}{\text{MHz}} \right) \left(\frac{\nu_c}{\text{GHz}} \right)^{-3} \text{ ms.} \quad (2.6)$$

When planning our observations, we need to take into account Eq. 2.6 and to choose a frequency resolution $d\nu$ that will allow us to mitigate the intra-channel smearing. This will, however, influence the smallest time resolution dt we can use, as the two are reciprocally constrained by the STFT.

2.2 Single Pulse Searches

Figure 2.2 shows the typical steps of a single pulse search. In the following subsections we discuss each step separately.

2.2.1 RFI Mitigation

All the human made transmissions such as mobile phone communications, radars, TVs, satellite telemetries, radio towers, etc. can severely corrupt the data recorded by a radio telescope. As a whole, they are generally defined as Radio Frequency Interference (RFI). RFI is a de facto omnipresent problem for all the operating radio telescopes in the World. Not even modern telescope built in radio quiet zones (e.g. remote deserts) totally fulfil the purpose of *RFI avoidance*. RFI signals, as being of terrestrial origin, are in most cases remarkably stronger than the astrophysical signals of interest and, without proper mitigation, they can severely harm the results of pulsar/FRB search. RFI can be broadly classified as they manifest themselves in the time domain or in the frequency domain. Time domain RFI can be persistent, impulsive and periodic whereas in the frequency domain it can be narrow-band (the most common case) and/or broad-band.

Throughout the years several mitigation techniques have been developed and all them are based on trying to exploit the statistics behind the data and the fact that RFI is a $\text{DM} = 0 \text{ pc cm}^{-3}$ phenomenon. In the frequency domain, the commonly used RFI mitigation techniques require to assume a certain statistics of the frequency spectrum (most of the times Gaussian or χ^2). We then define a certain threshold above which we assume that all the frequency channels with a spectrum value exceeding such threshold are RFI. A simple example of RFI mitigation in frequency, assuming for instance a Gaussian statistics for the frequency spectrum, is searching for frequency channels above several standard deviations from the mean of the spectrum. Modern algorithms exploits higher statistical moments of the data such as the Spectral Kurtosis Algorithm (Nita and Hellbourg, 2020; Nita and Gary, 2010) or the Inter-Quartile Range Mitigation (Morello, Rajwade, and Stappers, 2022) since they are more robust against drastic variation of the spectrum baseline.

In the time domain, when the signal has not yet been dedispersed, all the excesses of the time series are in most cases due to RFI and threshold techniques can be used with high confidence that we are not excising bins in which the astrophysical signal is present.

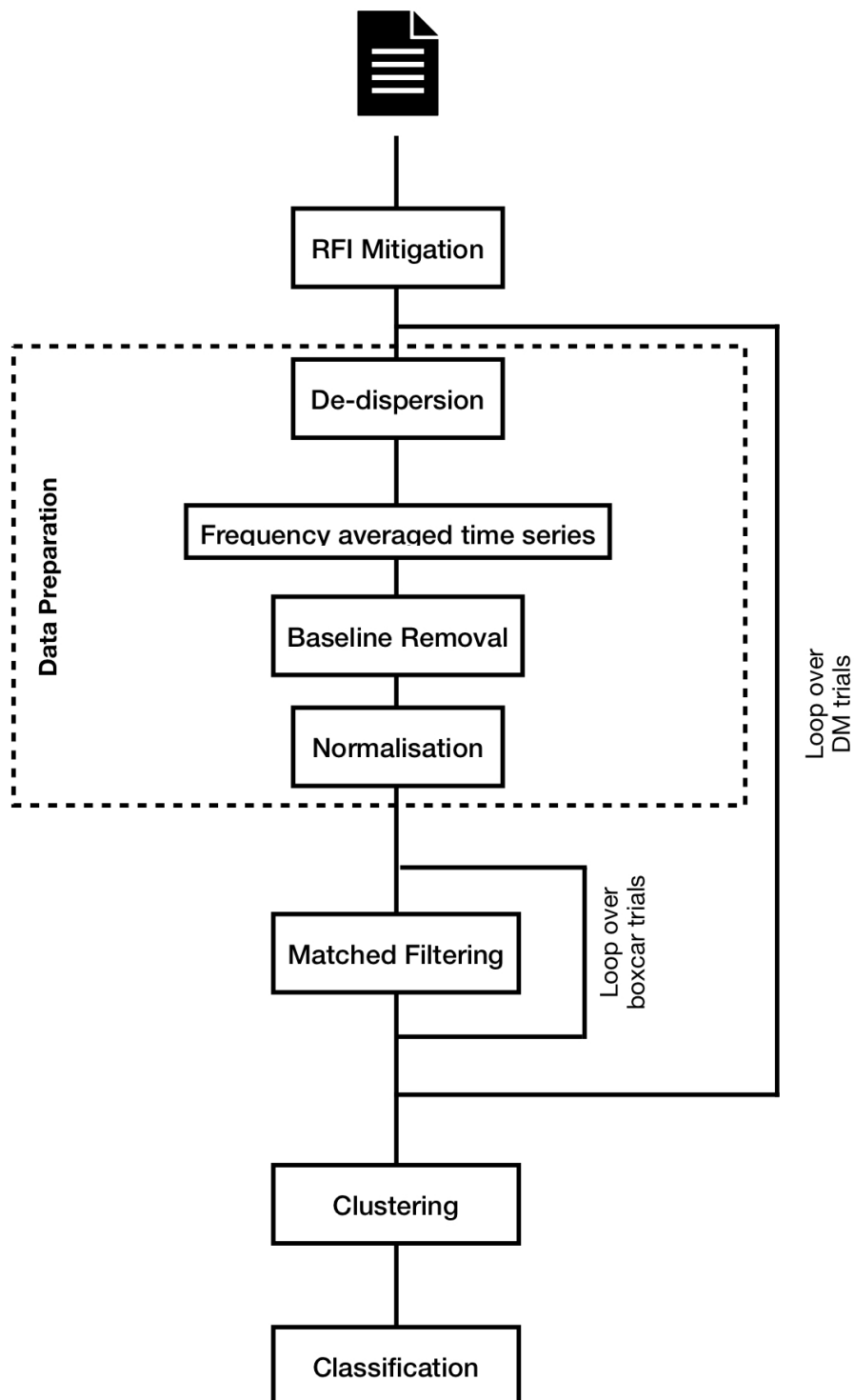


Figure 2.2: A general flow-chart of how single pulse searches are performed.

If we have a channelised spectrogram, a frequently used technique is the *zero DM subtraction* (Eatough, Keane, and Lyne, 2009) which consists of subtracting, in each row of the spectrogram matrix F_n^α , the frequency averaged time series (not dedispersed) $\sum_{\alpha=0}^{N_c} F_n^\alpha / N_c$.

2.2.2 Data Preparation

Before starting the search of pulses the data need to be initially prepared. If the DM of the FRB is known, as explained in Sec. 2.1 the data can be initially coherently dedispersed and the next steps of the search can be done only once. In the most frequent case of unknown DM, it is necessary to explore a sequence of N_{DM} DM trial values within an initially decided interval. The steps of the DM trials are chosen as a balance of the following criteria: if they are too small, it will remarkably increase the computation time of the search and it might not significantly improve the detection performances; conversely, if they are too large, it is possible to miss the FRB because of too much smearing. An approximated formula for the size of the i -th DM trial step δDM_i is (Lorimer and Kramer, 2005, Chap. 6):

$$\delta\text{DM}_i = 1.205 \times 10^{-7} (i - 1) dt \frac{\nu_M^3}{\nu_{\text{high}} - \nu_{\text{low}}} \text{ pc cm}^{-3}, \quad (2.7)$$

where dt is time resolution (in ms) of the search mode data matrix, $\nu_{\text{high}}, \nu_{\text{low}}$ are the highest and lowest observational frequencies (in MHz) considered and $\nu_M = (\nu_{\text{high}} + \nu_{\text{low}})/2$.

After being dedispersed the data matrix is averaged along the frequency axis, yielding a time series. To remove baseline variations which can degrade the search sensitivity, the baseline itself is estimated from the time series. This can be done via smoothing algorithms such as a Gaussian or a Savitzky-Golay filter smoothing or via running means or medians of the time series. The estimated baseline is then removed from the time series. Typical baseline windows are 1 to a few seconds long to not lose sensitivity for typical ms-width FRB events. Lastly the baseline-corrected time series is normalised, usually by its standard deviation or by the Median Absolute Deviation (MAD).

2.2.3 Matched Filtering

The time series is now ready to be searched for potential candidates. The most established technique for the search of single pulses is the matched filtering search (Cordes and McLaughlin, 2003): the time series is convolved with n trial top-hat functions each with width (*boxcar*) $W_n = 2^n$ bins. If the *signal-to-noise ratio*, S/N , of one of the boxcar convolved signals exceeds the decided threshold, the candidate is saved. Since we are using trial widths, in most cases, the S/N of the candidate thus determined is not accurate: supposing for instance that we have a burst of ~ 45 bins, if we explore the width space with powers of 2 (as it is usually done), that candidate, if detected, would have a S/N computed considering a width of 32 bins. We point out that spanning the boxcar width space logarithmically is not, per se, mandatory: in principle exploring this space linearly would be indeed more cautious since it would allow not to miss events with widths between two large boxcars. However, it would dramatically increase the computational time. Exploring for instance, the width space between 1 bin and 1000 bins, using powers of 2 as widths requires 10 trials against a 1000 trials for a linear scale.

2.2.4 Events Clustering

When the search of candidates is done, after having explored the whole DM/boxcar trial space, all the information (time of the candidate, DM trial, boxcar width and, possibly, pointings for phased array telescopes) of the candidates with $S/N > \text{threshold}$ are stored. A single event, if is particularly strong or the DM/boxcar space is sampled with quite small steps, it is usually detected several times at different, but close, values of DM/boxcar. It is convenient to group these redundancies (*clustering*) into a single candidate. Grouping of candidates is usually done in the DM and time space with clustering algorithms such as friends-of-friends (Barsdell, 2012; Huchra and Geller, 1982) or DBSCAN (Ester et al., 1996). The common idea behind these algorithms is to define a radius in the parameter space and group all the candidates within this radius, repeating this for all the points. After the clustering procedure has been done, the candidate with best S/N is taken as representative of that cluster.

2.2.5 Candidates Classification

All the steps previously described are the minimal and necessary stages to make a single pulse search successful. These steps are performed by established single pulse search softwares such as Heimdall (Barsdell et al., 2012) or `single_pulse_search.py` from PRESTO (Ransom, Eikenberry, and Middleditch, 2002). The candidates produced by a search software then typically undergo human classification and are, in the case of a positive result, reported. However, due to the large number of observations with high-time resolution performed in recent days, and due to the presence of the ever-growing number of RFI signals, the number of candidates produced per survey by a single pulse search software can easily exceed the thousands, if not millions, and only a very small percentage of them ($< 1\%$) are potential astrophysical candidates. Checking each candidate is becoming an unbearable task for a single or a group of humans. It is then necessary to try to automatise the classification step in order to leave to the human classification a manageable number of candidates. A powerful way to distinguish FRB genuine detections from RFI is by exploiting Convolutional Neural Networks (CNNs) to make image classification. Examples of CNNs applied in this way are reported in the work of Connor and van Leeuwen (2018) and the publicly available software FETCH of Agarwal et al. (2020). In order to recognise a genuine FRB from a RFI via CNN image classifier it is essential to use the right images to make the classification. Connor and van Leeuwen (2018) suggests to use three images as the training set (generated from both true and simulated events): the spectrogram of the dedispersed burst, the frequency averaged time series and the so called DM-time or “*butterfly*” plot. The DM-time plot is a 2 dimensional matrix D_n^ρ , each row ρ contains the frequency averaged time series of the candidate but dedispersed at a different trial DM. To make an example if a candidate has a DM of 400 pc cm^{-3} a reasonable DM-time plot can be generated in the range $300\text{--}500 \text{ pc cm}^{-3}$, as shown by the example in Fig. 2.3. From Fig. 2.3 we see that the signal is strong at the right DM and the signal loses strength when not dedispersed at the right DM, making this characteristic butterfly-shaped image. The DM-time plot is the strongest signature of an FRB, being an extra-galactic signal. It is difficult for RFI to mimic such an image as this will appear, most of the time, as a bright signal in all the DM-channels. Agarwal et al. (2020) showed that the DM-time plot and the dedispersed spectrogram signal are sufficient, since the frequency averaged time series gives redundant information already captured by the spectrogram.

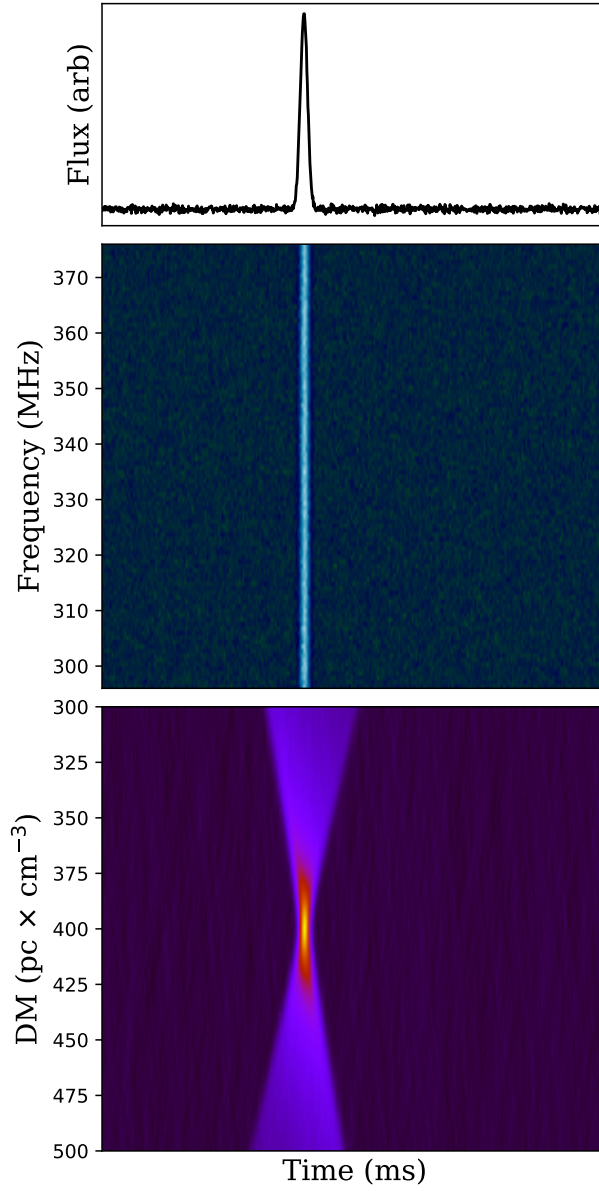


Figure 2.3: A simulated FRB. The top panel is the frequency averaged time series, the central panel is the dynamic spectrum of signal and the bottom panel shows a clearly visible signature in the DM-time, often called “butterfly”, plot.

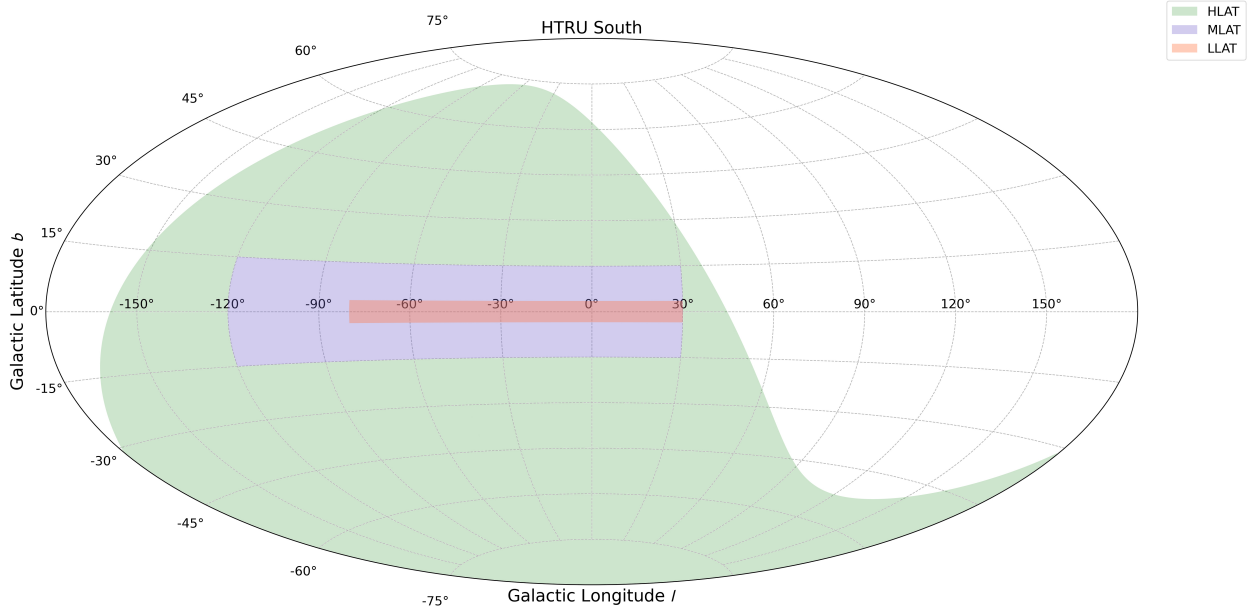


Figure 2.4: Sky coverage (Aitoff projection) of the HTRU survey Southern hemisphere performed by the Parkes telescope.

2.3 A Study Case: The HTRU Survey

2.3.1 Overview

The High Time Resolution Universe (HTRU, Keith et al., 2010) is an all sky survey, started in 2008 and ended in 2014, performed with the aim of having a better comprehension of the millisecond pulsar population and with the goal of confirming the physical nature of the millisecond duration radio transients as what was at the time a single representative of the now known population of FRBs: the LB.

The HTRU survey consisted of two parts: one carried out with by the 64-m single dish radio telescope of Parkes in Australia which covered the Southern hemisphere of the Sky (HTRU South) and the other made by the 100-m single dish Effelsberg telescope in Germany to cover the Northern Sky (HTRU North). In this work we will focus only on HTRU South and we will leave the readers to Barr (2011) and Barr et al. (2013) for a complete overview of the observational setup and strategy for HTRU North.

The HTRU South is in turn divided into three parts, which cover three different regions of the Sky: the **low-latitude** (LLAT) part, which covers the Sky area of Galactic longitude $-80^\circ < l < +30^\circ$ at Galactic latitudes $-3.5^\circ < b < +3.5^\circ$, hence a thin strip of the Galactic Centre; the **mid-latitude** (MLAT) part, which comprises the region of $-120^\circ < l < +30^\circ$ and $-15^\circ < b < +15^\circ$ and lastly the **high-latitude** (HLAT), which covers the entire region of the Southern Sky with declination $\delta < 10^\circ$. Figure 2.4 shows the sky coverages of the three parts.

The three parts of the survey have the same observational setup with the difference of the duration of a single observation and the total number of observations, chosen in a way to optimise the survey timeline and the scientific purposes: LLAT is designed for the search of weak high-DM pulsars in the Galactic plane, MLAT for bright millisecond pulsars potentially applicable for pulsar-timing arrays and HLAT mainly for the search of radio transients. The survey parameters are reported in Tab. 2.1.

Table 2.1: Observational setup of the three parts of the HTRU survey Southern hemisphere.

	HLAT	MLAT	LLAT
Sky Coverage	$\delta < 10^\circ$	$-120^\circ < l < +30^\circ$ $-15^\circ < b < +15^\circ$	$-80^\circ < l < +30^\circ$ $-3.5^\circ < b < +3.5^\circ$
Observation Duration (s)	270	540	4300
Observations	34099	7312	1230
Number of beams	13	13	13
Sampling time (μ s)	64	64	64
Central Frequency (MHz)	1382	1382	1382
Observational Bandwidth (MHz) ^(a)	400	400	400
Channel Bandwidth (kHz)	390.625	390.625	390.625
Number of Channels	1024	1024	1024
Total Data Size (TB)	435	190	250

(a) Due to the presence of a strong satellite RFI at the top of the observational band the effective bandwidth is ~ 340 MHz.

2.3.2 System Acquisition

The data have been recorded with the Parkes 21-cm multi-beam receiver system (PMB, Staveley-Smith et al., 1996). The PMB consists of 13 feeds centred around the prime focus of the Parkes antenna organised as two concentric hexagons as depicted in Fig. 2.5. The PMB records data at the central frequency of 1382 MHz and provides an observational bandwidth of 400 MHz. Due to the presence of a strong RFI from the Thuraya 3 communications satellite in the range 1525-1559 MHz a low-pass filter restricts the effective bandwidth to ~ 340 MHz. The HTRU data are recorded as 2 bits total-intensity search-mode data SIGPROC filterbanks.

2.3.3 Major Discoveries

HTRU South produced a plethora of results both from the search of new pulsars, with a long series of articles (Bates et al., 2011; Keith et al., 2012; Burke-Spolaor et al., 2012; Bates et al., 2012; Burgay et al., 2013; Levin et al., 2013; Tiburzi et al., 2013; Ng et al., 2014; Bates et al., 2015; Ng et al., 2015; Cameron et al., 2018; Morello et al., 2019; Burgay et al., 2019; Cameron et al., 2020; Sengar et al., 2022), and from the discovery, as we already mentioned in Sec. 1.1.1, of a population of radio transients with the seminal work of Thornton et al. (2013) which disambiguated, in a definitive way, the physical, and furthermore extra-galactic, nature of the FRBs. In their work, they processed 24 % of the HLAT survey, discovering four FRBs with DMs ranging from 553 to 1103 pc cm^{-3} , with Galactic latitudes $|b| > 41^\circ$. For the four bursts, DM predictions from the NE2001 model are about 3-6 % of the measured DMs, strongly supporting the idea of the most likely extra-galactic nature of FRBs. In the subsequent years, Champion et al. (2016) completed the processing of the HLAT, detecting five new bursts in addition to the four previously discovered. Petroff et al. (2019) detected an additional burst accidentally missed by Champion et al. (2016) because a small fraction of the HLAT data (~ 0.5 %) had not been correctly processed due to some job failures of the gSTAR supercomputer in use. Figure 2.6 shows the ten FRBs in HLAT of the three works.

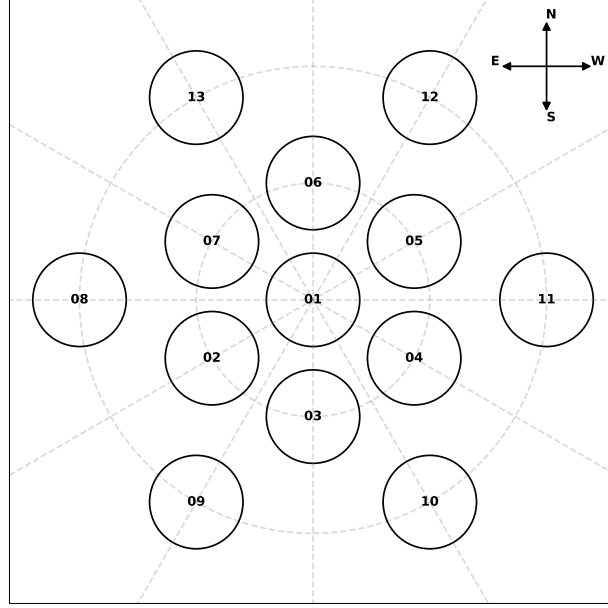


Figure 2.5: Geometry of the multi-beam receiver of the Parkes telescope. The diagram presents the feed configuration as projected onto the sky when the feed angle is 0° and the telescope is observing on the northern meridian. Note that the East and West directions are flipped (image adapted from: <https://www.atnf.csiro.au/research/multibeam/lstavele/description.html>).

2.4 The Search for narrow-band FRBs in HTRU South (Original Contribution)

2.4.1 Motivations

As discussed in Chap. 1, current experimental evidence shows that some FRBs can be extremely narrow-band signals, contrary to what we observe with pulsars, as we have seen from the blatant case reported by Kumar et al. (2021a).

This motivated others (see e.g. Pleunis et al., 2021, Sec. 4.3) to search in the data by following Kumar et al. (2021a) prescriptions. Figure 2.7 shows an intuitive diagram of how the sub-banded search is performed.

The idea behind this technique is simple. Let us consider a search-mode dataset, which is in general a $N_c \times N_s$ matrix with N_c frequency channels rows and N_s time bins columns. We suppose for simplicity that N_c is an integer power of 2 (this is mostly the case since the data are channelised in this way by the STFT as it is computationally more efficient). The search of bursts is then done, first to the full matrix, and then with gradually smaller and smaller data chunks. If we call Z the level of sub-banding, their width is going to be $N_c \times 2^{-Z}$ or, in physical units, $BW \times 2^{-Z}$ where $BW = N_c d\nu$ is the observational bandwidth and $d\nu$ is the frequency resolution. The level of sub-banding is arbitrary and it has to be decided considering how much large is the observing bandwidth and the increase of computational time. As we can see from Fig. 2.7, in order not to miss events which can occur between two adjacent sub-bands, also an overlapping sub-banding search is performed. For a level Z , the total numbers of searches N_{search} can be easily computed:

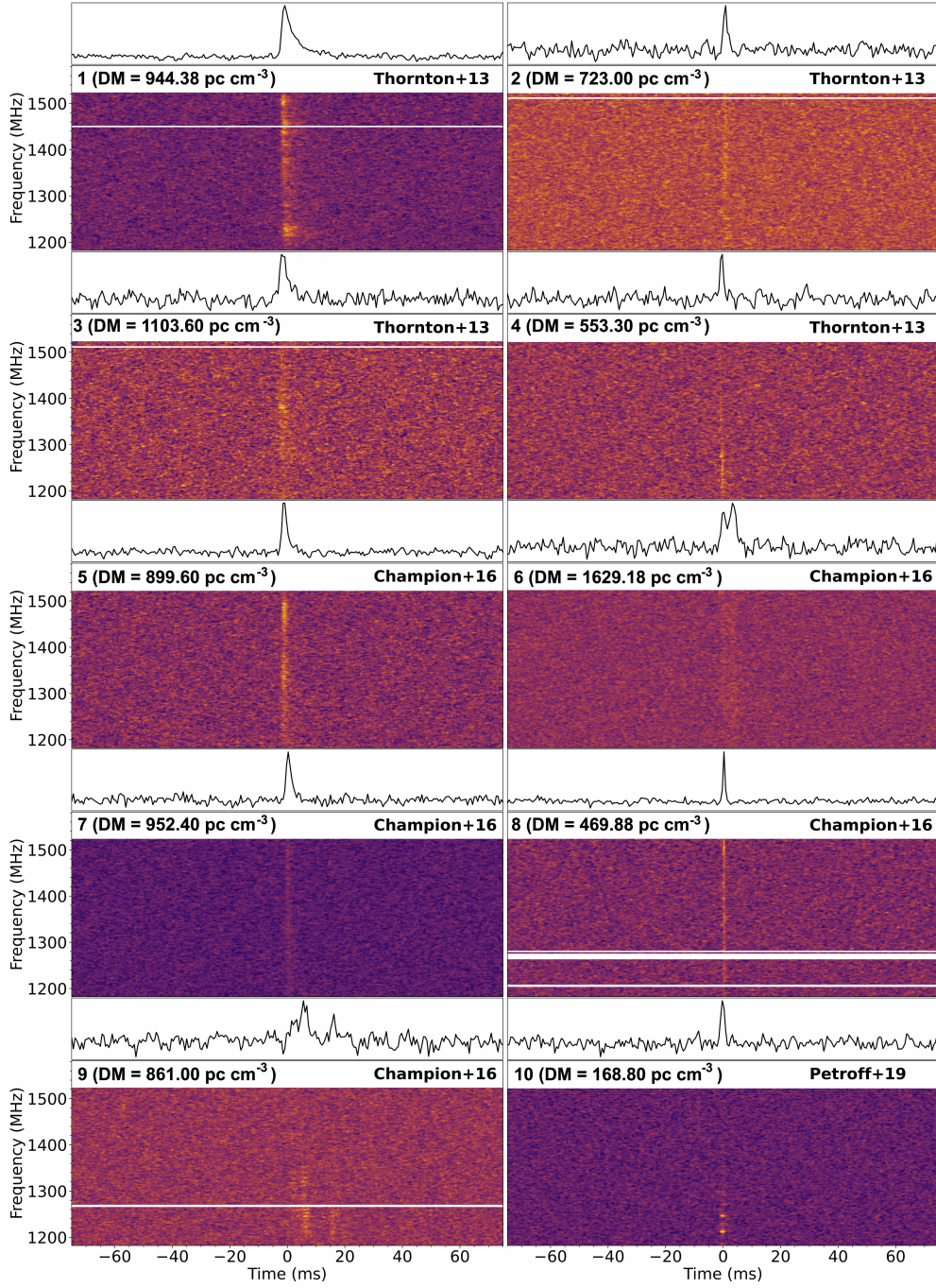


Figure 2.6: Replotting of the FRBs discovered by Thornton et al. (2013), Champion et al. (2016), and Petroff et al. (2019). For each burst, the top panel shows the frequency averaged time series of the signal and the bottom panel the waterfall plot. The blank rows are excised frequency channels due to RFI.

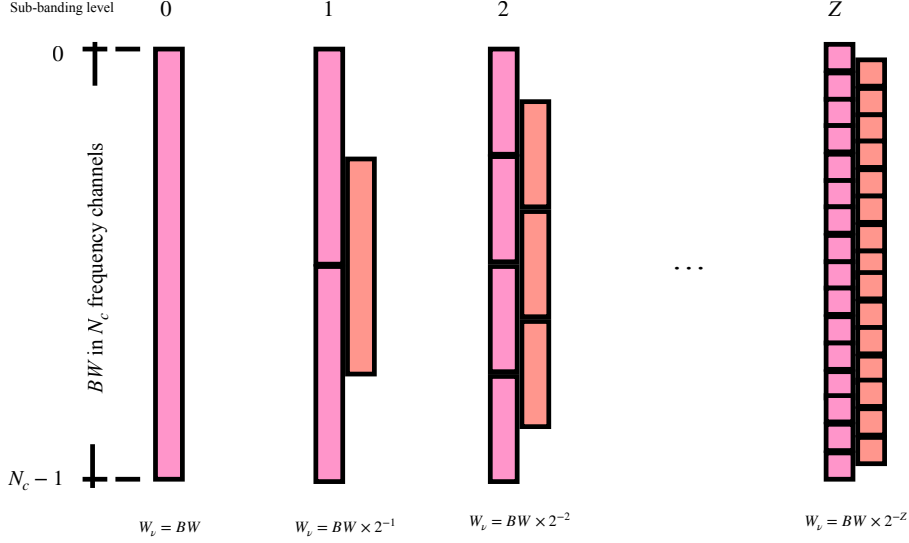


Figure 2.7: Scheme of the algorithm deployed to sub-band the search mode data.

$$N_{\text{search}} = \sum_{k=0}^Z (2^{k+1} - 1) = 2^{Z+2} - (Z + 3) . \quad (2.8)$$

The reason for such a search consists in the fact that events with a given full-band S/N could be below the detection threshold and missed by the search pipeline. In contrast the same event, in a given sub-band, could have a sub-band S/N above threshold and positively detected. This was indeed the case of the Kumar et al. (2021a) burst from the repeater FRB 20190711A, with a spectral width of ~ 65 MHz, which is $\sim 2\%$ of the 3.3 GHz Parkes UWL bandwidth. The authors reported a detection S/N of ~ 11.7 in a sub-band of 128 MHz. However, they did not assess how much S/N was gained with this strategy. In the following sections we will quantify how much S/N can be gained via this kind of searches. Motivated by the results, we re-processed the HTRU HLAT survey via this method and we will report our findings.

2.4.2 Signal-to-Noise Ratio Enhancement

Let us suppose we have a time series f_n (with $n = 0, 1, \dots, N_c N_s - 1$) of duration T . The series is transformed into a $N_c \times N_s$ matrix F_l^α (with $\alpha = 0, 1, \dots, N_c - 1; l = 0, 1, \dots, N_s - 1$) via a STFT (in the frequency range $\nu_c \pm BW/2$). We take the modulus square and incoherently de-disperse it at the right DM value. Let suppose now that we know this matrix contains a candidate FRB. We can then decompose the matrix F_l^α as sum of two matrices:

$$F_l^\alpha = B_l^\alpha + N_l^\alpha , \quad (2.9)$$

where B_l^α contains only the FRB candidate signal and N_l^α is the noise matrix. We also suppose that, initially, the noise in the time series f_n is pure white Gaussian noise with zero mean and variance σ^2 , that is $\in \mathcal{N}(0, \sigma^2)$. We will have then, in the matrix N_l^α , N_s

Fourier spectra of N_c points; each of them will follow a Chi-square distribution χ^2 with two degrees of freedom with mean and variance $2N_c\sigma^2$, that is $\in N_c\sigma^2\chi_2^2$ (Blackman and Tukey, 1958). In order to describe the FRB signal in the spectro-temporal domain contained in the matrix B_l^α it is more convenient to approximate B_l^α as a continuous real function $B(\nu, t)$, as $N_c \gg 1$ and $N_s \gg 1$. A reasonable first approximation model for a dedispersed FRB is a Gaussian function of the kind:

$$B_l^\alpha \simeq B(\nu, t) = Ae^{-\frac{(\nu-\nu_0)^2}{2\sigma_\nu^2}} e^{-\frac{(t-t_0)^2}{2\sigma_t^2}}, \quad (2.10)$$

where A is the amplitude which will regulate the intensity of the signal, ν_0, σ_ν are the central frequency of emission and standard deviation in frequency of the burst and t_0, σ_t are the time of arrival and standard deviation in the time of occurrence of the burst.

As we mentioned in Sec. 2.2.3, an important parameter to determine the burst significance is the S/N of the frequency averaged profile

$$p_l = \frac{1}{N_c} \sum_{\alpha=0}^{N_c-1} F_l^\alpha. \quad (2.11)$$

We recall here the S/N definition for a profile p_l :

$$S/N = \frac{1}{\varepsilon_{\text{off}} W_{\text{eq}}} \sum_{l=0}^{N_s-1} (p_l - \mu_{\text{off}}) \quad (2.12)$$

where $\mu_{\text{off}}, \varepsilon_{\text{off}}$ are the mean and standard deviation of the profile p_l off-pulse, and

$$W_{\text{eq}} = \frac{1}{p(z_{t_0})} \sum_{\text{on pulse}} (p_l - \mu_{\text{off}}), \quad (2.13)$$

where $z_{t_0} = [t_0/dt]$ is the corresponding discrete time bin of t_0 . We now *want to evaluate how much S/N we can gain considering*, rather than all the channels N_c , *a window W_c (or $W_\nu = W_c d\nu$ in physical units) as close as possible to the exact observed frequency width of the FRB.*

As a conventional consideration, we discuss now what we mean with physical widths, in time and frequency, of an FRB. Due to the complex structure they exhibit, as discussed in Sec. 1.2.11, there can be some arbitrariness when trying to define the burst width unambiguously. The most common convention, assuming the burst is reasonably Gaussian bell-like, is to take the Full Width at Half Maximum (FWHM) both in time and frequency. Hence according to Eq. 2.10 in our case the physical widths of the burst are:

$$\Delta t = 2\sqrt{2 \ln 2} \sigma_t, \quad (2.14)$$

$$\Delta \nu = 2\sqrt{2 \ln 2} \sigma_\nu. \quad (2.15)$$

When we sub-band the data and make the burst search we aim that our window W_ν be as close as possible to $\Delta \nu$.

From now on, we identify the quantities computed considering sub-band of the data using an asterisk *. We want to evaluate how much the S/N^* improves in comparison to the full-band one. To make this computation, we will evaluate step-by-step the various elements in Eq. 2.12.

Let us start with the average profile p_l . Substituting Eq. 2.11 in Eq. 2.9:

$$p_l = \frac{1}{N_c} \sum_{\alpha=0}^{N_c-1} (B_l^\alpha + N_l^\alpha) . \quad (2.16)$$

Let us treat the noise and signal separately. Within the noise contribution we are summing N_c random variables distributed as $N_c \sigma^2 \chi_2^2$. By exploiting properties of χ^2 random numbers we can write:

$$\frac{1}{N_c} \sum_{\alpha=0}^{N_c-1} N_l^\alpha \sim \frac{1}{N_c} \sum_{\alpha=0}^{N_c-1} N_c \sigma^2 \chi_2^2 = \sigma^2 \chi_{2N_c}^2 \sim \mathcal{N}(2N_c \sigma^2, 4N_c \sigma^4) . \quad (2.17)$$

We used the property that the sum of D $\chi_{d_i}^2$ independent variables with d_i degrees of freedom each is a $\chi_{\sum_i d_i}^2$ variable with $\sum_i d_i$ degrees of freedom and also the propriety of the χ^2 distribution for large degrees of freedom $\lim_{d \rightarrow \infty} \chi_d^2 \sim \mathcal{N}(d, 2d)$, that is for large d it can be well approximated by a Gaussian distribution with mean d and variance $2d$. Making a notation abuse, we evaluate now the burst term treating it as continuous limit:

$$\frac{1}{N_c} \sum_{\alpha=0}^{N_c-1} B_l^\alpha \simeq \frac{1}{BW} \int_{\nu_0 - BW/2}^{\nu_0 + BW/2} B(\nu, t) d\nu \simeq \frac{1}{BW} \int_{-\infty}^{+\infty} B(\nu, t) d\nu = \sqrt{2\pi} A \frac{\sigma_\nu}{BW} e^{-\frac{(t-t_0)^2}{2\sigma_t^2}} , \quad (2.18)$$

where we extended the integral to the infinity since we assume that the burst frequency width is smaller than the observational bandwidth. The average profile in the full-band, p_l , is hence a Gaussian function in time, modelled as Eq. 2.18 with each time bin corrupted by a white noise $\in \mathcal{N}(2N_c \sigma^2, 4N_c \sigma^4)$.

In a similar fashion we can now compute the average profile considering a sub-band:

$$p_l^* = \frac{1}{W_c} \sum_{\alpha=z_{\nu_0}-[W_c/2]}^{z_{\nu_0}+[W_c/2]} F_l^\alpha = \frac{1}{W_c} \sum_{\alpha=z_{\nu_0}-[W_c/2]}^{z_{\nu_0}+[W_c/2]} (B_l^\alpha + N_l^\alpha) , \quad (2.19)$$

where $z_{\nu_0} = [\nu_c/d\nu]$ is the corresponding discrete frequency channel of ν_0 . Handling the burst and the noise separately we can conclude analogously to what we did in Eq. 2.17 that the sub-banded profile noise will follow the statistics:

$$\frac{1}{W_c} \sum_{\alpha=z_{\nu_0}-[W_c/2]}^{z_{\nu_0}+[W_c/2]} N_l^\alpha \sim \mathcal{N}\left(2N_c \sigma^2, 4W_c \left(\frac{N_c}{W_c}\right)^2 \sigma^4\right) , \quad (2.20)$$

and the sub-banded FRB profile can be obtained via an integral:

$$\frac{1}{W_c} \sum_{\alpha=z_{\nu_0}-[W_c/2]}^{z_{\nu_0}+[W_c/2]} B_l^\alpha \simeq \frac{1}{W_\nu} \int_{\nu_0 - W_\nu/2}^{\nu_0 + W_\nu/2} B(\nu, t) d\nu \quad (2.21)$$

$$\simeq \sqrt{2\pi} A \frac{\sigma_\nu}{W_\nu} e^{-\frac{(t-t_0)^2}{2\sigma_t^2}} \quad (2.22)$$

Similarly to the full-band profile, we obtain a Gaussian function in time corrupted by white noise.

As the next step we show that the equivalent width is the same in both cases:

$$W_{\text{eq}} = \frac{1}{p(z_{t_0})} \sum_{\text{on pulse}} (p_l - \mu_{\text{off}}) \simeq \frac{1}{p(z_{t_0})} p(z_{t_0}) \Delta t = \Delta t , \quad (2.23)$$

hence when will consider the ratio between S/N^* and S/N that can be directly simplified. The standard deviations of the profile off-bursts are, thanks to Eqs. 2.17 and 2.20:

$$\begin{aligned} \varepsilon &= 2\sqrt{N_c} \sigma^2 \\ \varepsilon^* &= 2\sqrt{W_c} \left(\frac{N_c}{W_c} \right) \sigma^2 . \end{aligned} \quad (2.24)$$

We need to evaluate the sum of the profile:

$$I = \sum_{l=0}^{N_c} (p_l - \mu_{\text{off}}) . \quad (2.25)$$

Again, assuming the profile as continuous function, we can approximate the sum as an integral:

$$I \simeq \int_0^T p(t) dt \simeq \int_{-\infty}^{+\infty} p(t) dt = \sqrt{2\pi} A \frac{\sigma_\nu}{BW} \int_{-\infty}^{+\infty} e^{-\frac{(t-t_0)^2}{2\sigma_t^2}} dt = 2\pi A \frac{\sigma_\nu}{BW} \sigma_t , \quad (2.26)$$

and, in an analogue way, for the sub-banded profile:

$$I^* \simeq \int_0^T p^*(t) dt \simeq \int_{-\infty}^{+\infty} p^*(t) dt = 2\pi A \frac{\sigma_\nu}{W_\nu} \sigma_t . \quad (2.27)$$

Lastly, considering Eq. 2.12 for both profiles and taking the ratio:

$$S/N^* \simeq \frac{I^*}{\varepsilon^*} \frac{\varepsilon}{I} S/N = \sqrt{\frac{BW}{W_\nu}} S/N . \quad (2.28)$$

In conclusion, if we select a sub-band whose width resembles the spectral extension of an FRB, we can have a gain in S/N of the order of $\sqrt{BW/W_\nu}$. If for instance a burst is present only on the top or bottom half part of the bandwidth and has a $S/N \sim 7$ its S/N^* can be ~ 1.4 larger in its half-band becoming hence more significant with $S/N^* \sim 10$.

The results above are unsurprising, given the adopted simple approximation of a dedispersed FRB structure with a Gaussian shape, both in frequency and in time. As anticipated in the paragraph before 2.14 and 2.15, that approximation rarely holds true exactly. However our detailed analytical derivation above is useful to formalise predictions to be compared with real data; in fact, as presented later, in many cases those predictions show a good enough agreement with the outcome of the data analysis.

2.4.3 Pipeline Description

In order to process the remarkable amount of data (~ 0.4 PB) of the survey, we built a dedicated pipeline which is summarised in Fig. 2.8. The processing of the data has been performed using the OzSTAR supercomputer¹ installed at the Swinburne University in Australia. Each observation is split into 13 SIGPROC filterbank files, each for a single beam of the PMB receiver. Once retrieved a single filterbank file, we perform the following steps:

¹<https://supercomputing.swin.edu.au/ozstar/>

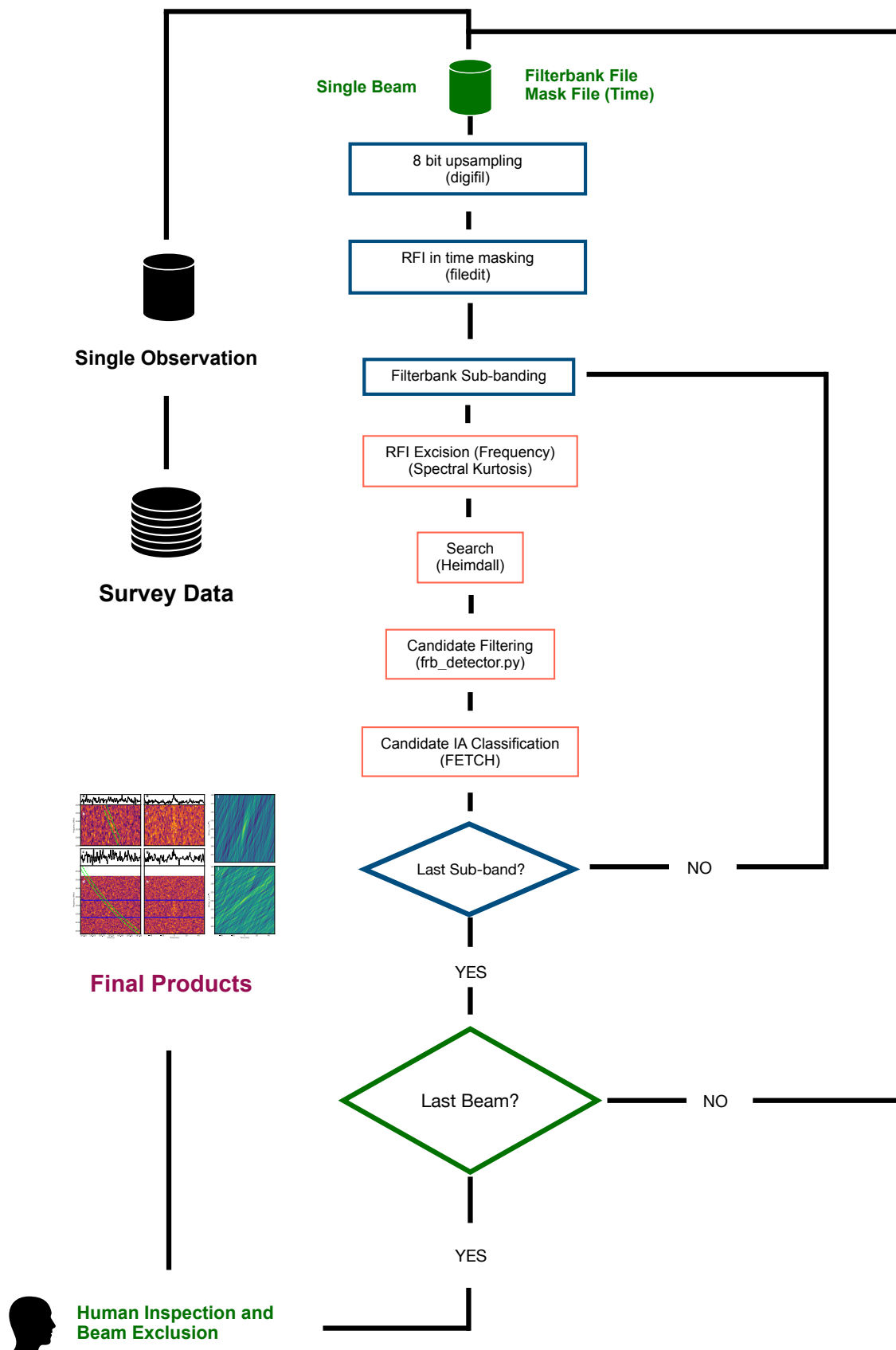


Figure 2.8: Flow chart of the sub-band search pipeline deployed to process the HTRU survey.

1. **File Upsampling.** As a first step, the filterbank file is upsampled from a 2 bits file to a 8 bits file by using the software routine `digifil` from the `DSPSR` software package (van Straten and Bailes, 2011). This step was necessary since some softwares employed in the following steps require (at least) 8-bit filterbank files.
2. **RFI Excision in Time.** Each filterbank file is accompanied by an associated RFI mask which contains the bin number of the most contaminated time bins which were previously assessed. Each corrupted bin is substituted with a random Gaussian number drawn from the distribution of the un-corrupted time bins. This operation has been performed via the `filedit` routine from `SIGPROC`.
3. **File sub-banding.** Each file is sub-banded according to the procedure that was outlined in Sec. 2.4.1 and we considered $Z = 2$ as the maximum level of sub-banding, which yielded the following configuration of sub-bands: 1×400 MHz, 3×200 MHz, 7×100 MHz. For each sub-band we then process the data according to the following steps:
 - *RFI Excision in Frequency.* For each sub-banded file we search for the noisiest channels present in the spectrum. We adopted a Spectral Kurtosis algorithm, as the one described in Sec. 2.2.1, provided by the python package `YOUR` (Aggarwal et al., 2020). We considered a 5σ threshold. As we mentioned in Sec. 2.3.2 ~ 60 MHz of the top band is known to be always affected by RFI., providing ~ 154 corrupted channels. These channels have been always flagged as zero.
 - *Single Pulse Search.* FRB candidates have been searched via the software package `Heimdall` (Barsdell et al., 2012). The search for candidates by `Heimdall` follows the steps we outlined in Sec. 2.2. Despite `Heimdall` performs its own RFI flagging we parsed the spectral channels also via the option `-zap_chans` to have a deep RFI purging in order to mitigate as much as possible the number of candidates (due to RFI) inevitably detected by the software. The data were searched in DM from 0 to 10000 pc cm^{-3} , over box-car widths from 0.128 ms (2 bins) to 262.144 ms (4096 bins).
 - *Candidates Filtering.* Before using an AI classification we made a pre-filtering to significantly reduce the sheer amount of candidates produced by `Heimdall` by matching the following criteria:

$$\begin{aligned}
S/N &\geq 7 ; \\
\text{DM} &\geq 10 \text{ pc cm}^{-3} ; \\
N_m &\geq 3 ; \\
N_{1s} &\leq 2 .
\end{aligned} \tag{2.29}$$

We filter then all the candidates produced by `Heimdall` which have a $6 \leq S/N < 7$ (`Heimdall` by default does not produce candidates with S/N less than 6), with a minimum number of “members” N_m of 3 which are the number of distinct box-car/DM trials clustered into a single candidate by `Heimdall` by its internal clustering algorithm and N_{1s} is the maximum number of candidates allowed in a window of 1 s. This procedure has been performed by using the software `frb_detector.py` (Barsdell et al., 2012).

- *Candidates AI Classification.* The candidates filtered according to the criteria in Eq. 2.29 are inspected by `FETCH`. `FETCH` has eleven CNN architectures available

(model a to k , each of them with a different choice of layers, see Agarwal et al. 2020). Each model, after classification, returns a probability p to be compared with a probability threshold p_{thres} for the candidate to be either a real event ($p > p_{\text{thres}}$) or RFI ($p \leq p_{\text{thres}}$). We used a threshold $p_{\text{thres}} = 0.5$ which is the default parameter. This will ensure that we do not miss weak events falsely classified as RFI, meaning that by-eye inspection will be performed in each case. We used only model a since, as reported by the authors, it is the most performing overall (Agarwal et al., 2020). We note that the initial 8 bits file upsampling was required by FETCH.

4. **Human Evaluation.** Lastly the candidates positively classified by FETCH are humanly evaluated. This step cannot be completely objective and there can be some systematic errors due to the arbitrariness of the decision making process. We describe the “plausibility” criteria we used. As a conservative approach all the candidates which showed bright clustered pixels, in the dynamic spectrum (additional to the clustered ones of the putative FRB candidate) have been discarded. Candidates with DM compatible with the Galactic DM predicted by using the NE2001 model and YMW16 for the beam sky direction are rejected. Candidates which appear in multiple not adjacent beams, according to Fig. 2.5, are not considered. For each promising candidate detected in a single beam we create and inspect the waterfall and DM-time plot of the candidate in the other 12 beams, in order to check if there are suspicious spurious signals missed by the pipeline, and again discard candidates which have clustered bright pixels in multiple not adjacent beams. To clearer let us make an example, supposing that for instance a candidate has been found in beam number 12 with a certain time of arrival and DM. We then check the data at that time, de-dispersing it at that DM in the other beam files to see if there are clustered bright pixels in the other waterfall plots. In the case of beam number 12, following the geometry of Fig. 2.5, if there are bright pixels also in the waterfalls produced in beams 06 and 05, the candidate could be taken into consideration. Conversely, if a similar candidate is present in beam number 09 then it is immediately discarded as Terrestrial RFI since only a Terrestrial source can be detected at the same time in such far away beam pointings. Supposing again that a similar candidate has been found in one of the adjacent beams, let us say beam number 06, we expect to see this candidate much fainter, as the case of the burst detected by Petroff et al. (2019). If the candidate is as bright as the one in beam 12 we again conclude that the candidate is RFI. We are looking for, and expecting, weak events. Aside for the extremely powerful event of the LB, it is quite unlikely for an FRB to be detected in multiple beams with a strong and clearly visible signal. We point that the first and the second adopted criteria can be extremely conservative and they can potentially lead to the discard of real events. In the first case some candidates could be indeed true and with an additional RFI excision they could be positively classified. In the second case we are only looking for extra-galactic events and we are discarding events like the ones produced by the SGR J1935+2154. Both cases will be subject to further inspection as of a future work.

2.4.4 Preliminary Results

Selected Candidates

After the whole processing Heimdall found about 6×10^9 candidates, with $\sim 10^7$ of them surviving the pipeline filtering as discussed in Sec. 2.4.3. Only $\sim 10^4$ of these were positively

classified by **FETCH**.

We then carefully performed human vetting of these 10^4 positively classified candidates. Out of the candidates found by **FETCH** a large fraction were single pulses (detected also in the full-band and/or recursive sub-bands) of already discovered pulsars² in the Southern Sky. We cross-checked them with the online ATNF pulsar catalogue, first compiled by Manchester et al. (2005), which provides an up-to-date list of the known pulsars. Other events were FRB-like events detected in multiple beams and thus discarded as RFI events.

Re-detected FRBs

Lastly we re-detected the 10 HLAT FRBs in several sub-bands. The S/N obtained in the several sub-bands contains some valuable information: the first burst from Thornton et al. (2013) is the strongest of the published bursts (as it can be visually assessed from Fig. 2.6), with a $S/N \sim 49$. This burst has been detected in the half sub-bands with a $S/N^* \sim 35$ and in the quarter sub-bands with $S/N^* \sim 24$ apart the ones which comprise the top band corrupted by the RFI telemetry. In this case we get a S/N loss rather than a S/N gain. The same applied to the fourth burst from Champion et al. (2016) which has a full-band $S/N \sim 30$ and was detected in the half sub-band with $S/N^* \sim 23$ and in the quarter sub-bands with $S/N^* \sim 14$. In contrast, the last burst of Champion et al. (2016) and the burst of Petroff et al. (2019) which have full-band S/N of ~ 14 and ~ 13 respectively have been detected in the lower half band with a $S/N \sim 17$, reasonably close to our prediction dictated by Eq. 2.28.

Except for the two aforementioned cases, all published bursts spectra extend in the full observational bandwidth. In this case, we can explain the S/N loss starting from Eq. 2.10. When the burst is totally extended in the full observational bandwidth, since $\sigma_\nu \sim BW$, we can make the assumption that $\sigma_\nu \gg 1$. At this point, we can Taylor expand Eq. 2.10 in ν/σ_ν at the first order obtaining:

$$B(\nu, t) \simeq Ae^{-\frac{(t-t_0)^2}{2\sigma_t^2}}, \quad (2.30)$$

that is, in each frequency channel we have a Gaussian function in time modelled by Eq. 2.30. This implies that in this case the expressions of I and I^* in Eqs. 2.26 and 2.27 are the same since the profiles $p(t)$ and $p^*(t)$ are the same. However the rms of the profile noise will be still described by Eqs. 2.20. Hence we have:

$$S/N^* = \frac{I^*}{\varepsilon^*} \frac{\varepsilon}{I} S/N = \frac{\varepsilon}{\varepsilon^*} = \sqrt{\frac{W_\nu}{BW}} S/N. \quad (2.31)$$

This confirms that if a burst is completely extended in the full observational band and it has a certain S/N , in an half sub-band the S/N^* will be worse of a factor of $1/\sqrt{2}$ or, in the case of a quarter of sub-band, will be half its full-band value. This finding is indeed compatible with the previously mentioned bursts of Thornton et al. (2013) and Champion et al. (2016) and it reasonably applies for all the 8 full-band HLAT bursts albeit with some discrepancies which can happen mainly for two reasons: for the presence of RFI and/or the fact that the burst model is too simple and it does not consider physical effects which can change the adopted fully Gaussian shape of the burst such as scintillation.

²<https://www.atnf.csiro.au/research/pulsar/psrcat/>

Plausibility of the other detected Candidates

Out of the 10^4 candidates which survived the **FETCH** selection, only 51 met the requirements described in the human vetting section of the pipeline. All the properties of the bursts detected are reported in Tab 2.2. The DM of the found candidates spans from a minimum of $\sim 125 \text{ pc cm}^{-3}$ to a maximum of $\sim 1650 \text{ pc cm}^{-3}$, always 2 – 30 times larger than the DM predictions of the Galactic contribution to their beam pointings (obtained by using the software package **pygedm**, Price, Flynn, and Deller (2021)).

We will now discuss the plausibility of these 51 candidates. The candidates are presented in Figs. 2.12-2.22. Starting from the bottom part of the plots, which represent the dynamic spectra of the dispersed data, we highlight with a dashed white line the ν^{-2} curve corresponding to the burst DM. In most cases, it is difficult to disentangle the possible FRB signal from these plots even in the sub-bands where the signal has been found. On the other hand, the top three plots, relative only to the selected sub-band, show more evident excesses, possibly representing a real source at an extragalactic distance.

We first discuss the probability that these bursts are simply due to random excesses in the frequency averaged time series. Cordes and McLaughlin (2003) showed that, for a time series of N_s samples, the average number of false detections $n_{\text{false}}(> S/N)$ by chance due only to noise, for a single DM trial and above a certain S/N is:

$$n_{\text{false}}(> S/N) \simeq 2N_s P(> S/N) , \quad (2.32)$$

where

$$P(> S/N) = \int_{S/N}^{+\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} = \frac{1}{2} \left[1 - \text{erf} \left(\frac{S/N}{\sqrt{2}} \right) \right] , \quad (2.33)$$

and

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} dz , \quad (2.34)$$

is the error function. When processing a survey of N_{point} pointings of N_{beam} each and searching for bursts via a sub-banded search of level Z the total number $N_{\text{false}}(> S/N)$ of false detection above a threshold S/N is:

$$N_{\text{false}}(> S/N) = 2N_{\text{beam}}N_{\text{points}}N_s P(> S/N) \Pi [Z, N_{\text{DM}}(\nu_{\text{top}}, \nu_{\text{bot}})] , \quad (2.35)$$

where Π is a factor which takes into account the number of sub-bands in which we searched for candidates which will have a respective number of trials N_{DM} since, as discussed in Sec. 2.2.2, the optimal number of DM trials also depends on the top and bottom observational frequencies $\nu_{\text{top}}, \nu_{\text{bot}}$:

$$\Pi [Z, N_{\text{DM}}(\nu_{\text{top}}, \nu_{\text{bot}})] = \sum_{k=0}^Z \sum_{\text{sub-bands}} N_{\text{DM}}(\nu_{\text{top}}, \nu_{\text{bot}})^{(Z)} . \quad (2.36)$$

Figure 2.9 shows the expected number of false detections $N_{\text{false}}(> S/N)$ due to noise as a function of the threshold S/N . Our candidates span in sub-banded signal-to-noise ratio from 7 (which was the minimum allowed by our filtering criteria) to 12. According to the prediction, we notice that, starting from a S/N exceeding 8.5, the whole processing of the survey should produce less than 1 candidate by chance due to the noise. As already mentioned in Sec. 2.2.1, however, the presence of RFI can significantly affect the prediction of Eq. 2.35. Assessing how much RFIs can increase this number of false detections would require a complete knowledge of the RFI environment which corrupted the data which,

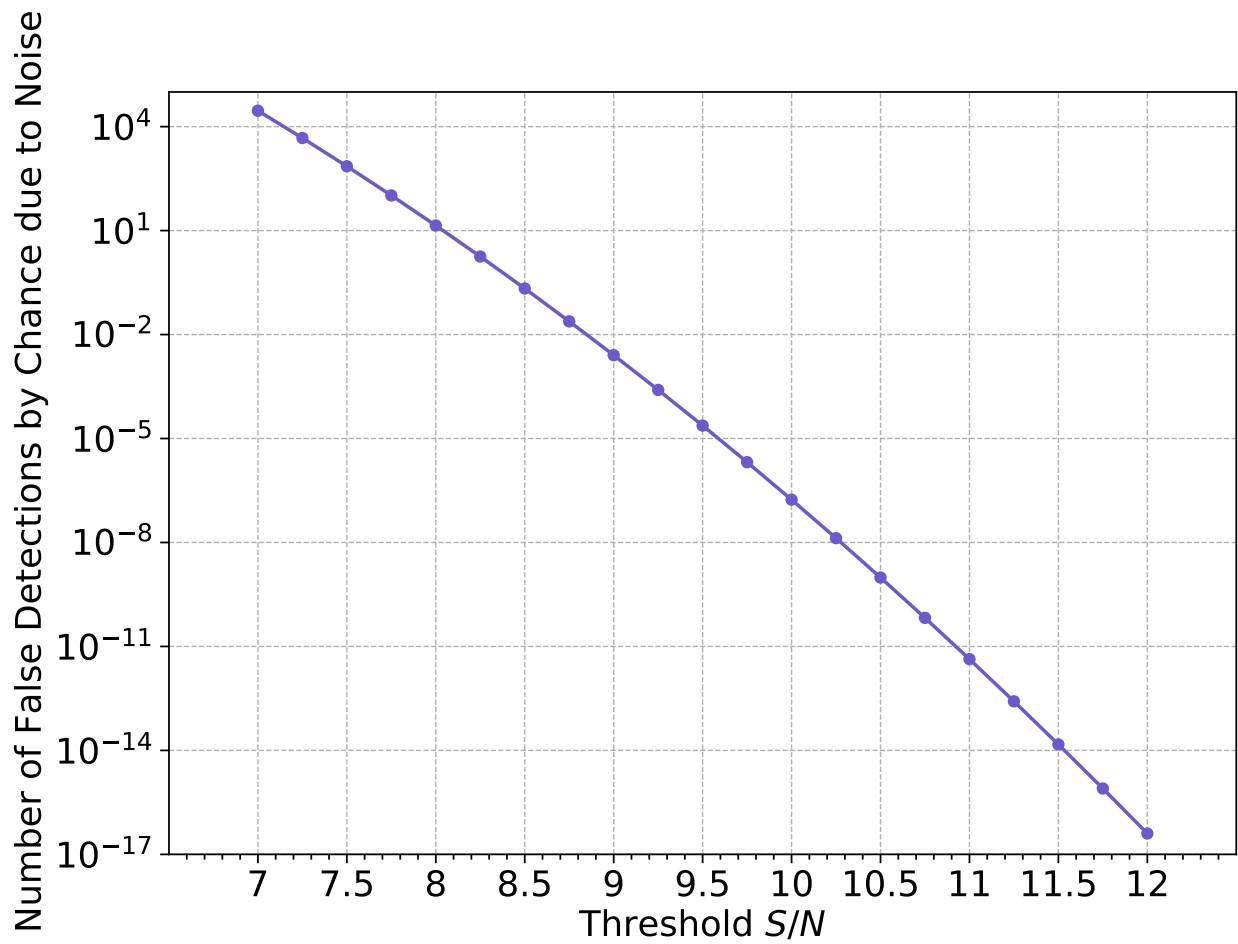


Figure 2.9: Number of false detections by chance due to only noise as a function of the threshold S/N ($Z = 2$).

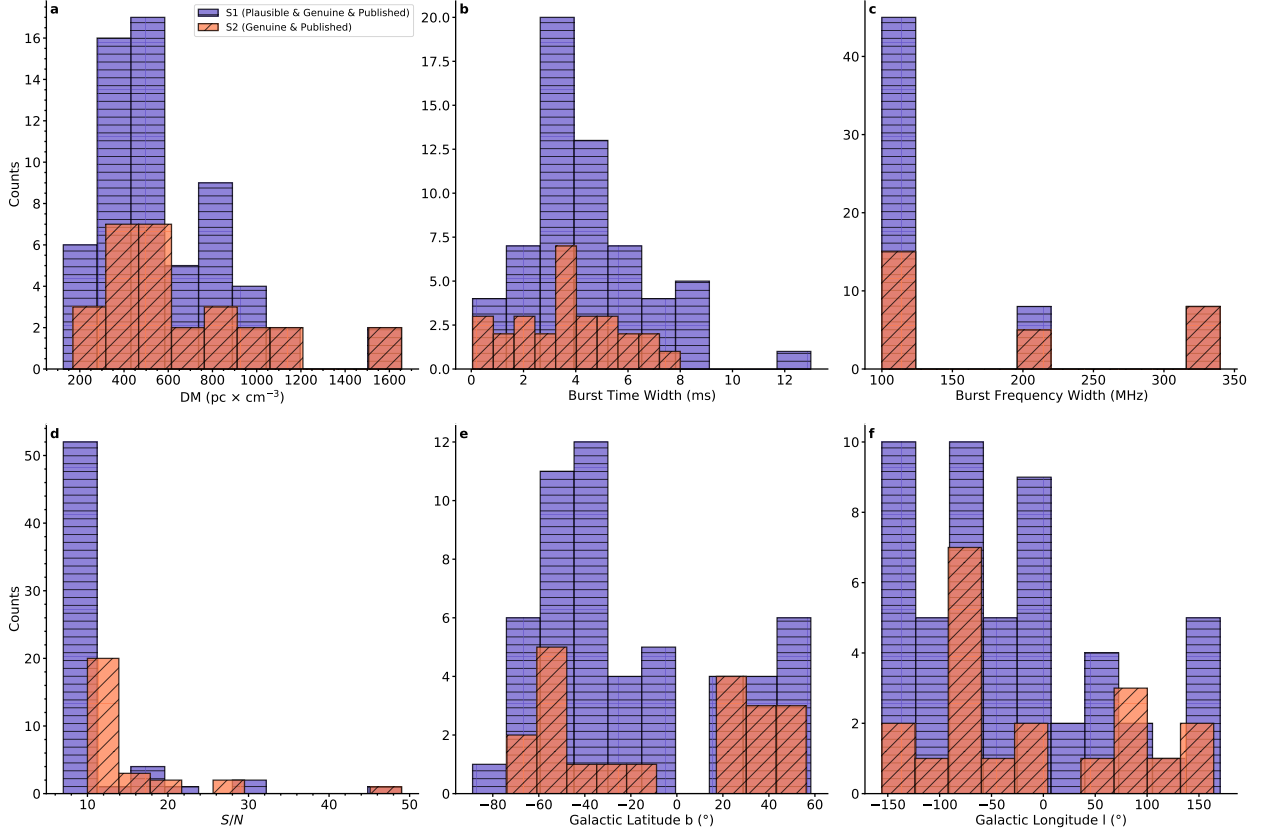


Figure 2.10: Distributions of DM (a), time width (b), frequency width (c), S/N (d), Galactic Latitude b (e) and Galactic Longitude l (f) of the plausible and genuine candidates plus the already published HLAT FRBs (S1, violet bars, Thornton et al., 2013; Champion et al., 2016; Petroff et al., 2019) and of the genuine candidates and already published (S2, coral bars).

in almost all the cases, is not possible. A reasonable approach is then to raise the S/N threshold for what is to be classified, by human inspection, as real candidates. For our survey, a threshold of 10 implies $\sim 10^{-7}$ false detections and, even supposing that that RFI increases the number of false detections by 7 orders of magnitude we should expect order of one false alarm detections. Another important aspect to be considered is the prediction quality of the classifier. As stated by the authors, **FETCH** has a recall³ above 99 % for a S/N exceeding 10. For these reasons, we consider as **genuine** detections only the candidates with $S/N \geq 10$ (18/51 of our candidates) while the rest of the candidates have been labelled as **plausible** since the the classifier for $S/N < 10$ is less reliable.

Parameter Distributions

Figure 2.10 shows the distribution of DM (a), time width (b), frequency width (c), S/N (d), Galactic latitude (e) and Galactic Longitude (f) of two samples of bursts: the first sample comprises the whole 51 candidates detected plus the already published HLAT bursts (S1); the second sample consists of the candidates labelled as genuine and the HLAT published bursts (S2). For the S/N distribution we used the highest S/N , either sub-band or full-band,

³In binary classification Recall is the fraction between the number of true events correctly identified by the classifier (True Positives, TP) and the sum of the true positives and the number of false events mistaken for true event (False Positives, FP), that is $\text{Recall} = \text{TP} / (\text{TP} + \text{FN})$

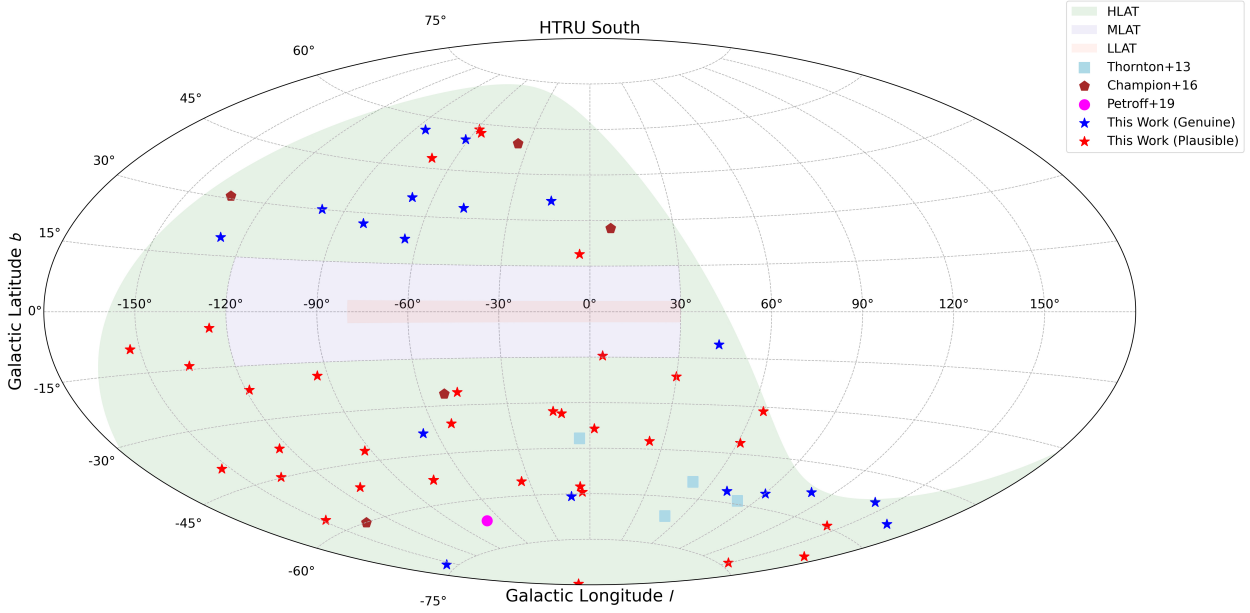


Figure 2.11: Sky distribution of the bursts detected in this work (the genuine are blue and the plausible are red) detected in the sub-banded search of HTRU HLAT. As comparison also the bursts from Thornton et al. (2013), Champion et al. (2016), and Petroff et al. (2019) have been plotted.

depending on which was larger.

Despite the limited size of the samples, which contain 61 elements (S1) and 28 elements (S2), respectively, it is appealing to discuss how the data are distributed and make some comparisons with the distribution of bursts (536 FRBs, 62 of which are bursts from 18 different repeating sources) of the CHIME/FRB catalogue (The CHIME/FRB Collaboration et al., 2021).

Regarding the DM distribution, from Fig. 2.10, we see for both S1 and S2 that the distributions tend to peak at $\sim 500 \text{ pc cm}^{-3}$, similarly to the one obtained by CHIME with a log-normal distribution. Also in the case of the time width distribution, with a peak around widths of 3 – 4 ms rather than several tens of ms, there are similarities with the one of CHIME. On the other hand, the frequency width distribution for S1 highly favours events at lower bandwidths, while S2 seems to be more uniformly distributed. The frequency distribution reported by CHIME has a larger number of events at the full-band of 400 MHz. This corroborates the idea that a fraction of the plausible candidates could not be real events. The number of candidates, both for S1 and S2, rapidly decreases for increasing S/N values, however it is not easy to establish if the decrease follows a power law as expected by the fluence distribution of FRBs (The CHIME/FRB Collaboration et al., 2021), due to the small sample we possess. The last two histograms of Fig 2.10, as well as Fig 2.11, show the sky distribution of the beam pointings of the detected bursts. The distributions are relatively uniform. We see lack of detections in the range $-15^\circ < b < 15^\circ$ which is consistent with how HLAT was designed, as discussed in Sec. 2.3.

2.4.5 Summary and Conclusion

In this work we reprocessed, via sub-banded searches, the HTRU Southern Hemisphere HLAT. We first computed how much S/N can be possibly gained via sub-banded searches and we showed that, if the burst resides only in a region W_ν of the observational bandwidth

BW , then the gain is $\sim \sqrt{BW/W_\nu}$. Via this sub-banded search we detected 18 new bursts with $S/N \geq 10$, almost twice the number of the previously detected bursts, and other 31 with $7 < S/N < 10$ which we labelled as plausible although less certain candidates. Combining our sample of 18 bursts with the previously bursts detected by Thornton et al. (2013), Champion et al. (2016), and Petroff et al. (2019), we have investigated the distributions in DM, time width, frequency width and S/N and compared with the distributions reported by The CHIME/FRB Collaboration et al. (2021). However, the sample is still not large enough too make robust conclusions.

Table 2.2: Properties of the detected candidates in the sub-banded search of HTRU HLAT. Each candidate has an assigned ID (first column). The second column contains the time of arrival (TOA) of the candidates computed with respect the topocentric reference frame and at frequency $\nu_{\text{top}} = 1582 \text{ MHz}$, the third and fourth columns contains the R.A. and Dec. beam pointings respectively where the burst occurred, the fifth column is the Heimdall DM (with a conservative 10 % error each) of the candidates, the sixth column contains the DM prediction of the Galactic contribution to the DM according to the NE2001 (Cordes and Lazio, 2002) and YMW16 (Yao, Manchester, and Wang, 2017) models, Δt is the FWHM width of the bursts computed via a Gaussian fit, W_ν is the sub-band frequency width of the burst in which has been found, S/N and S/N^* are the signal-to-noise ratio computed with respect to the full-band and the sub-band respectively. S is the peak flux density computed via the radiometer equation and F is the candidate fluence computed as $F = S \times \Delta t$, both values should be considered as lower limits since the peak flux density is computed with the radiometer equation considering the system temperature at the central beam of the PMB.

CandID	TOA $_{\text{topo}}^{\nu=\nu_{\text{top}}}$ (MJD)	R.A. ($hh : mm : ss$)	Dec. ($^\circ : ' : ''$)	DM (pc cm^{-3})	Galactic DM $_{\text{YMW16}}^{\text{NE2001}}$ (pc cm^{-3})	Δt (ms)	W_ν (MHz)	S/N	S/N^*	S (Jy)	F (Jy ms)
Genuine											
B01	56488.386616	12:15:30	-39:35:19	204.45	(84.50,79.70)	3.3 ± 0.4	200	8	12	> 0.5	> 1.5
B02	55672.962508	23:08:08	-04:34:28	248.05	(33.20,23.70)	6.1 ± 0.9	100	7	11	> 0.4	> 2.7
B03	55561.338024	02:01:16	-23:38:22	472.75	(29.50,22.20)	6.6 ± 0.9	100	8	11	> 0.4	> 2.8
B04	56662.790473	11:51:05	-03:22:38	394.83	(34.20,26.40)	6.1 ± 0.9	100	9	11	> 0.3	> 1.9
B05	56405.326536	08:37:35	-06:49:43	452.77	(72.10,67.00)	5.0 ± 0.8	100	5	11	> 0.3	> 1.7
B06	56653.889492	15:08:09	-15:04:36	527.46	(47.50,39.50)	4.7 ± 0.7	100	6	11	> 0.5	> 2.3
B07	56656.906695	19:48:05	04:03:47	458.56	(170.40,127.10)	3.9 ± 0.6	200	7	11	> 0.4	> 1.5
B08	56675.962208	13:29:20	-28:52:35	1078.69	(57.60,43.30)	4.9 ± 0.9	100	6	11	> 0.5	> 2.3
B09	56657.668195	11:10:48	-31:19:44	535.55	(66.50,73.80)	4.3 ± 0.7	100	6	11	> 0.4	> 1.5
B10	56632.742044	12:12:06	-26:18:36	396.57	(33.50,24.30)	3.8 ± 0.5	100	8	11	> 0.3	> 1.3
B11	56585.800067	10:21:11	-20:33:52	1655.13	(56.40,46.20)	7.0 ± 1.0	100	6	11	> 0.4	> 2.7
B12	56469.443399	12:41:18	-08:01:30	410.76	(34.70,25.70)	3.7 ± 0.6	100	7	11	> 0.5	> 2.0
B13	55981.277722	00:20:17	08:55:11	766.33	(32.90,24.40)	3.6 ± 0.6	100	4	10	> 0.4	> 1.3
B14	56124.013309	02:50:35	-76:50:34	681.53	(47.70,38.20)	8.0 ± 1.0	100	5	10	> 0.3	> 2.8
B15	56027.130313	01:39:46	09:23:19	534.82	(35.80,26.30)	2.8 ± 0.4	100	5	10	> 0.6	> 1.6
B16	55592.376355	02:20:52	00:46:01	546.06	(35.50,27.70)	3.9 ± 0.6	100	7	10	> 0.3	> 1.3
B17	56296.408940	23:40:57	02:33:27	371.38	(33.00,24.20)	2.1 ± 0.4	200	4	10	> 0.7	> 1.4
B18	56140.860458	22:53:07	-44:00:37	397.01	(33.90,21.80)	2.8 ± 0.5	100	5	10	> 0.6	> 1.6

Continue of Tab.2.2.

CandID	TOA $_{\text{topo}}^{\nu=\nu_{\text{top}}}$ (MJD)	R.A. ($hh:mm:ss$)	Dec. ($^{\circ} : ' : ''$)	DM (pc cm^{-3})	Galactic DM $_{\text{YMW16}}^{\text{NE2001}}$ (pc cm^{-3})	Δt (ms)	W_{ν} (MHz)	S/N	S/N^*	S (Jy)	F (Jy ms)
Plausible											
B19	56299.251741	20:14:51	-49:41:30	370.91	(60.00,43.50)	3.6 ± 0.5	100	4	9	> 0.3	> 1.2
B20	55590.519268	07:14:37	-55:32:41	413.63	(84.70,216.10)	3.4 ± 0.6	100	6	9	> 0.5	> 1.7
B21	55339.015819	22:30:58	-42:40:20	732.26	(35.60,23.30)	7.0 ± 1.0	100	7	9	> 0.2	> 1.7
B22	55333.841338	20:02:52	-11:59:50	543.01	(88.90,66.80)	4.0 ± 0.7	100	4	9	> 0.5	> 1.8
B23	56407.481547	12:48:03	-04:37:52	913.79	(32.90,24.00)	6.0 ± 1.0	100	7	9	> 0.2	> 1.4
B24	56292.258619	21:19:24	-23:55:37	469.54	(45.40,21.60)	4.1 ± 0.7	100	5	9	> 0.3	> 1.3
B25	55973.156050	22:39:40	-41:38:01	431.26	(34.60,22.40)	3.3 ± 0.6	100	6	9	> 0.3	> 1.1
B26	56029.992887	22:06:29	00:39:53	472.23	(40.00,30.20)	8.0 ± 1.0	100	6	9	> 0.2	> 1.8
B27	56407.064857	18:27:46	-80:53:58	316.09	(76.90,60.90)	3.0 ± 0.5	100	6	9	> 0.5	> 1.5
B28	54955.972158	01:20:37	-12:42:36	752.83	(30.00,24.50)	3.0 ± 0.5	100	5	9	> 0.4	> 1.1
B29	55926.531613	02:22:15	-61:12:52	818.04	(35.70,25.40)	4.9 ± 0.9	100	3	9	> 0.4	> 1.9
B30	56663.113710	18:54:43	-31:47:44	299.98	(160.20,103.50)	3.3 ± 0.6	100	4	9	> 0.5	> 1.6
B31	55045.797612	04:26:38	-57:32:05	503.34	(41.10,34.30)	6.0 ± 1.0	100	5	9	> 0.4	> 2.1
B32	56067.146548	06:20:43	-16:33:43	367.43	(88.70,134.10)	2.9 ± 0.5	100	4	9	> 0.4	> 1.0
B33	55540.373140	03:45:31	-43:28:02	667.50	(34.60,26.70)	6.0 ± 1.0	100	6	9	> 0.4	> 2.1
B34	56398.633467	16:29:03	-20:37:20	402.27	(111.30,80.50)	3.5 ± 0.7	100	5	9	> 0.3	> 1.1
B35	55976.189851	21:40:14	08:53:40	293.73	(48.50,38.80)	2.4 ± 0.5	100	4	9	> 0.4	> 0.9
B36	55758.001735	06:16:06	-34:00:37	730.98	(65.30,67.80)	9.0 ± 2.0	100	5	9	> 0.3	> 2.5
B37	56138.906072	01:30:31	01:41:53	829.44	(33.10,24.50)	8.0 ± 2.0	100	6	9	> 0.3	> 2.4
B38	55675.143846	04:54:30	-33:47:55	823.72	(41.80,37.90)	7.0 ± 1.0	100	4	8	> 0.2	> 1.4

Continue of Tab.2.2.

CandID	TOA $_{\text{topo}}^{\nu=\nu_{\text{top}}}$ (MJD)	R.A. ($hh:mm:ss$)	Dec. ($^{\circ} : ' : ''$)	DM (pc cm^{-3})	Galactic DM $_{\text{YMW16}}^{\text{NE2001}}$ (pc cm^{-3})	Δt (ms)	W_{ν} (MHz)	S/N	S/N^*	S (Jy)	F (Jy ms)
Plausible											
B39	55606.021759	20:08:51	-52:14:20	823.72	(61.60,44.50)	5.0 ± 1.0	100	7	8	> 0.4	> 1.9
B40	56659.766520	12:15:51	-13:49:25	234.44	(39.00,31.70)	9.0 ± 6.0	200	4	8	> 0.3	> 2.5
B41	56027.256666	07:15:10	-20:52:08	745.65	(176.20,313.80)	6.0 ± 1.0	100	5	8	> 0.3	> 2.0
B42	54938.086472	03:16:51	-21:50:00	338.87	(32.90,30.00)	4.0 ± 0.8	100	5	8	> 0.3	> 1.1
B43	56474.365672	12:53:00	-05:39:34	287.61	(33.50,24.40)	3.3 ± 0.6	100	5	8	> 0.3	> 0.9
B44	55332.010577	23:14:09	-57:10:14	570.46	(36.30,24.60)	3.4 ± 0.7	100	7	8	> 0.3	> 1.0
B45	55433.627035	00:56:55	-27:03:55	221.33	(28.50,18.80)	4.0 ± 1.0	200	5	8	> 0.2	> 1.0
B46	55678.080305	02:01:34	-10:06:40	475.32	(31.20,23.70)	2.5 ± 0.5	100	3	8	> 0.3	> 0.8
B47	55592.576837	06:07:45	01:19:02	304.22	(127.50,212.50)	2.4 ± 0.4	100	4	8	> 0.5	> 1.2
B48	56140.750572	20:47:10	-40:06:26	125.26	(51.00,36.60)	4.3 ± 0.8	200	7	8	> 0.3	> 1.1
B49	56128.834006	23:25:30	-80:38:43	506.86	(52.80,39.80)	3.2 ± 0.6	100	4	8	> 0.3	> 0.9
B50	55564.423848	04:15:05	-26:15:38	347.48	(37.30,35.40)	3.3 ± 0.7	100	5	7	> 0.3	> 0.9
B51	55908.592018	04:17:30	-12:30:14	771.88	(41.50,47.60)	13.0 ± 2.0	100	4	7	> 0.1	> 1.8

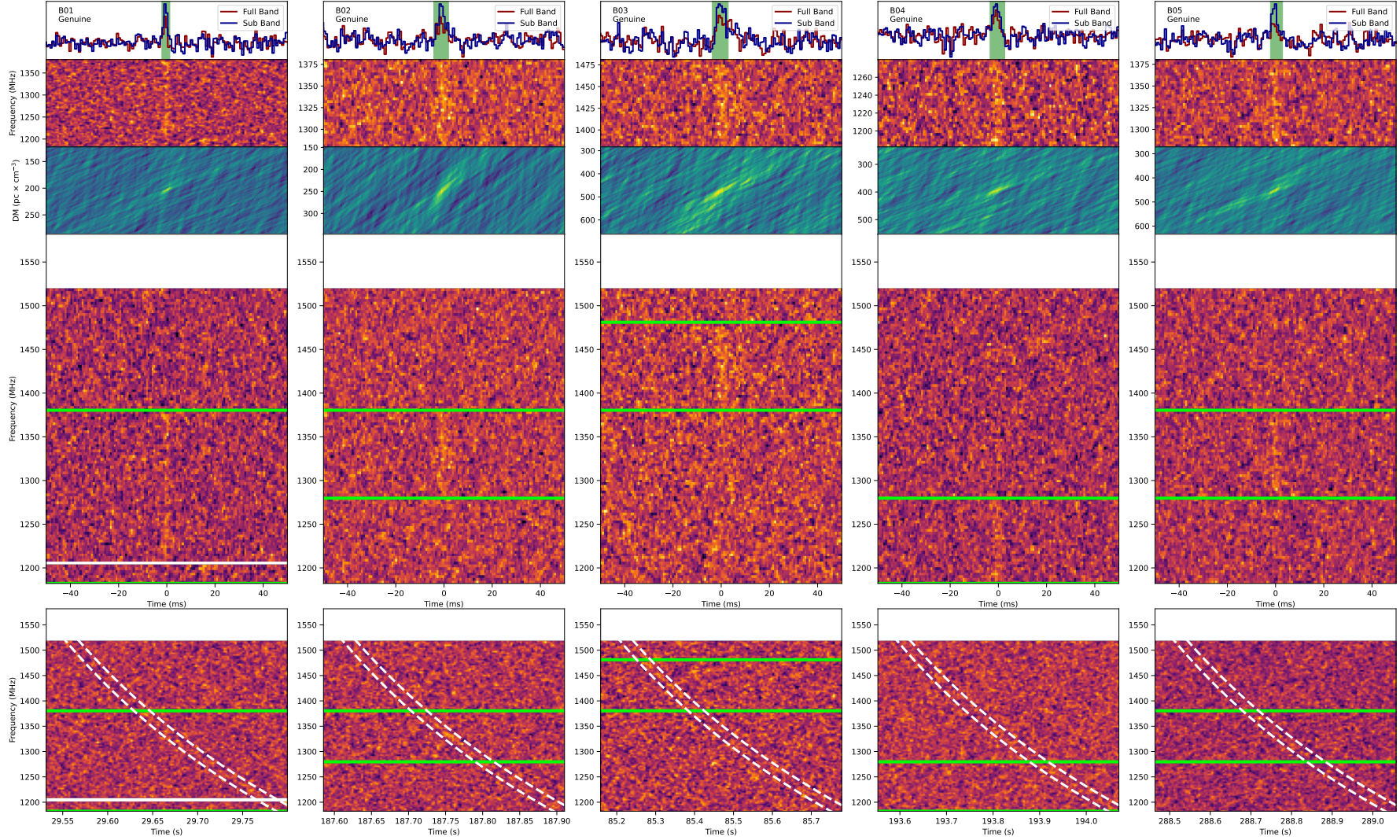


Figure 2.12: Narrow FRB candidates (tagged with genuine and plausible) in the HTRU HLAT sub-band search. For each burst, the bottom panel shows the dispersed waterfall plot of the data in which two white dashed curves guide the eye too see where the dispersed burst is supposed to be located and two green lines delimit the sub-band area in which the burst has been detected. The mid-lower panel shows the waterfall plot of the dedispersed data, the mid-central panel is the DM-time (butterfly) plot of the burst and the mid-upper panel is the waterfall plot of the sub-banded dedispersed data. Lastly the top panel shows the frequency averaged time series, averaging along the full band (red curve) and averaging along the sub-band (blue line). The blank rows in all the waterfall plots are excised channels due to RFI.

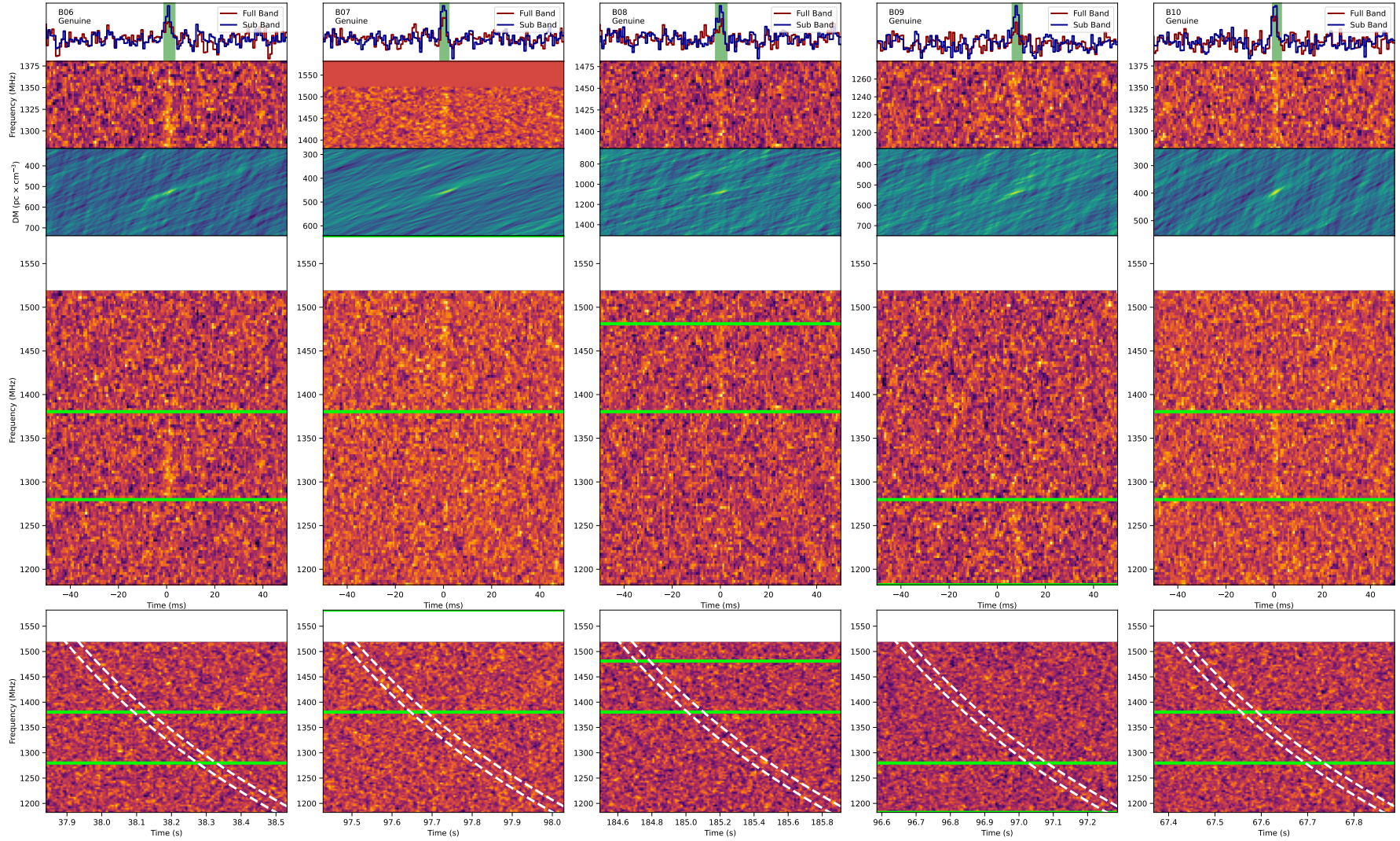


Figure 2.13: The same as Fig. 2.12 for B06-10.

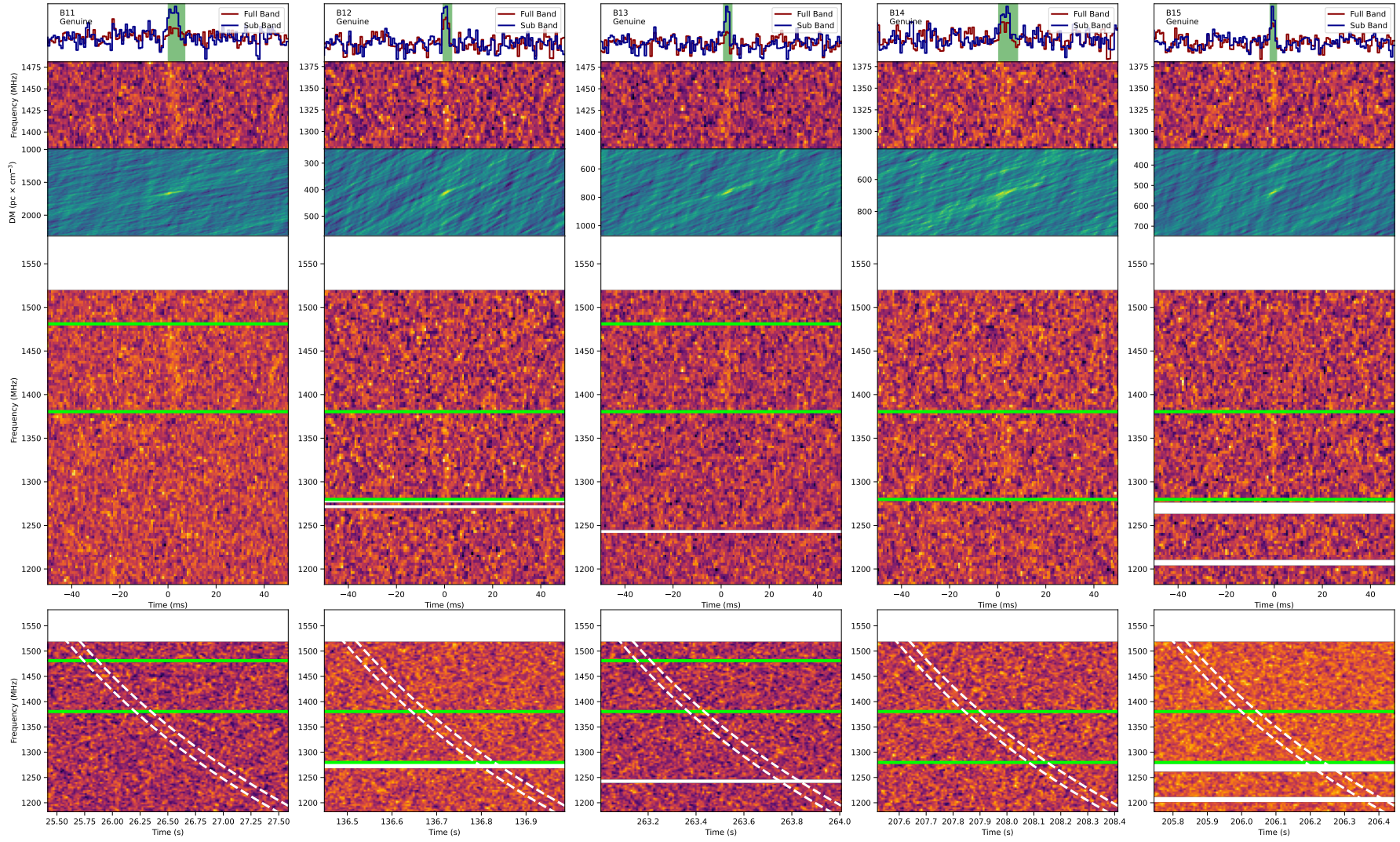


Figure 2.14: The same as Fig. 2.12 for B11-15.

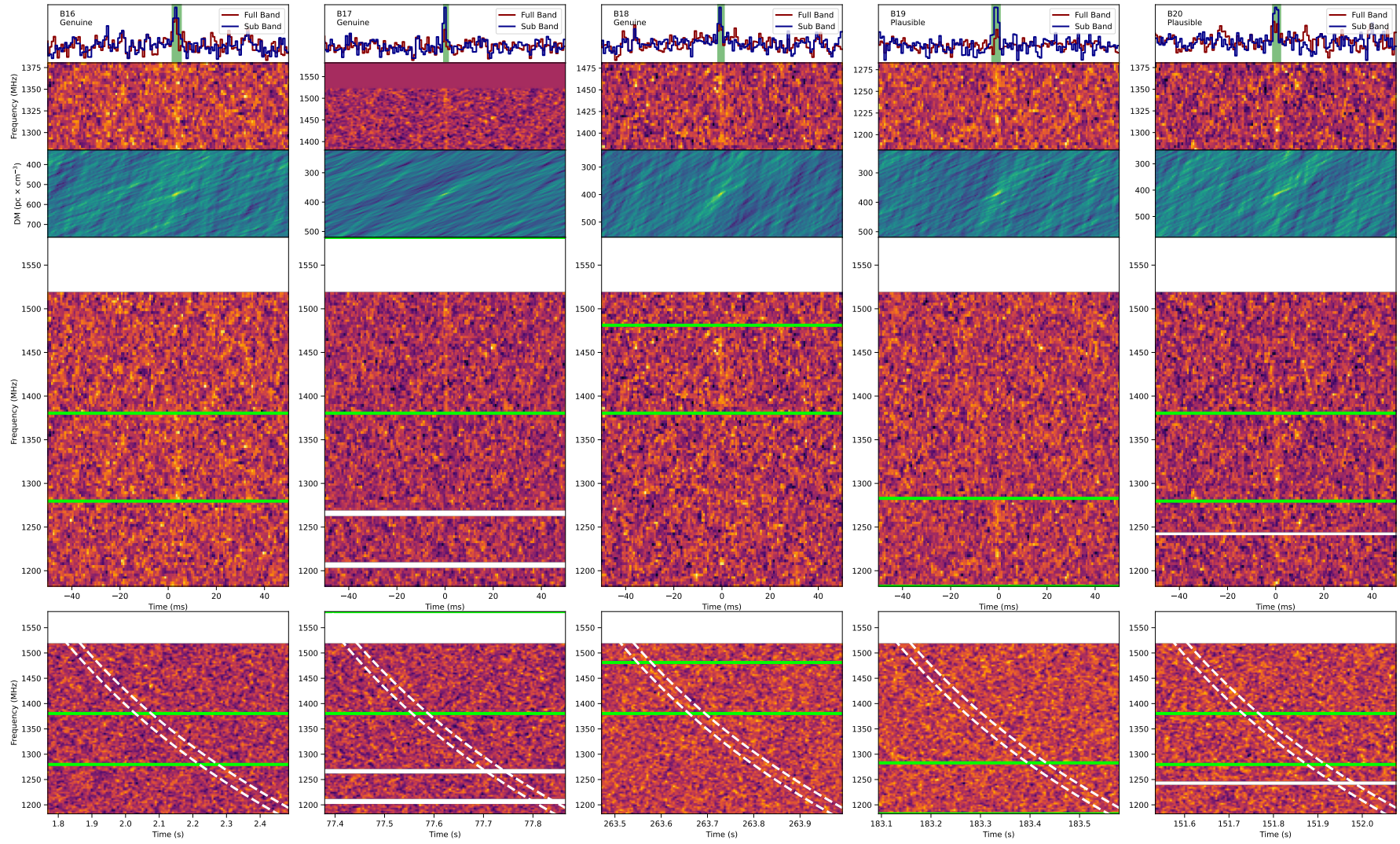


Figure 2.15: The same as Fig. 2.12 for B16-20.

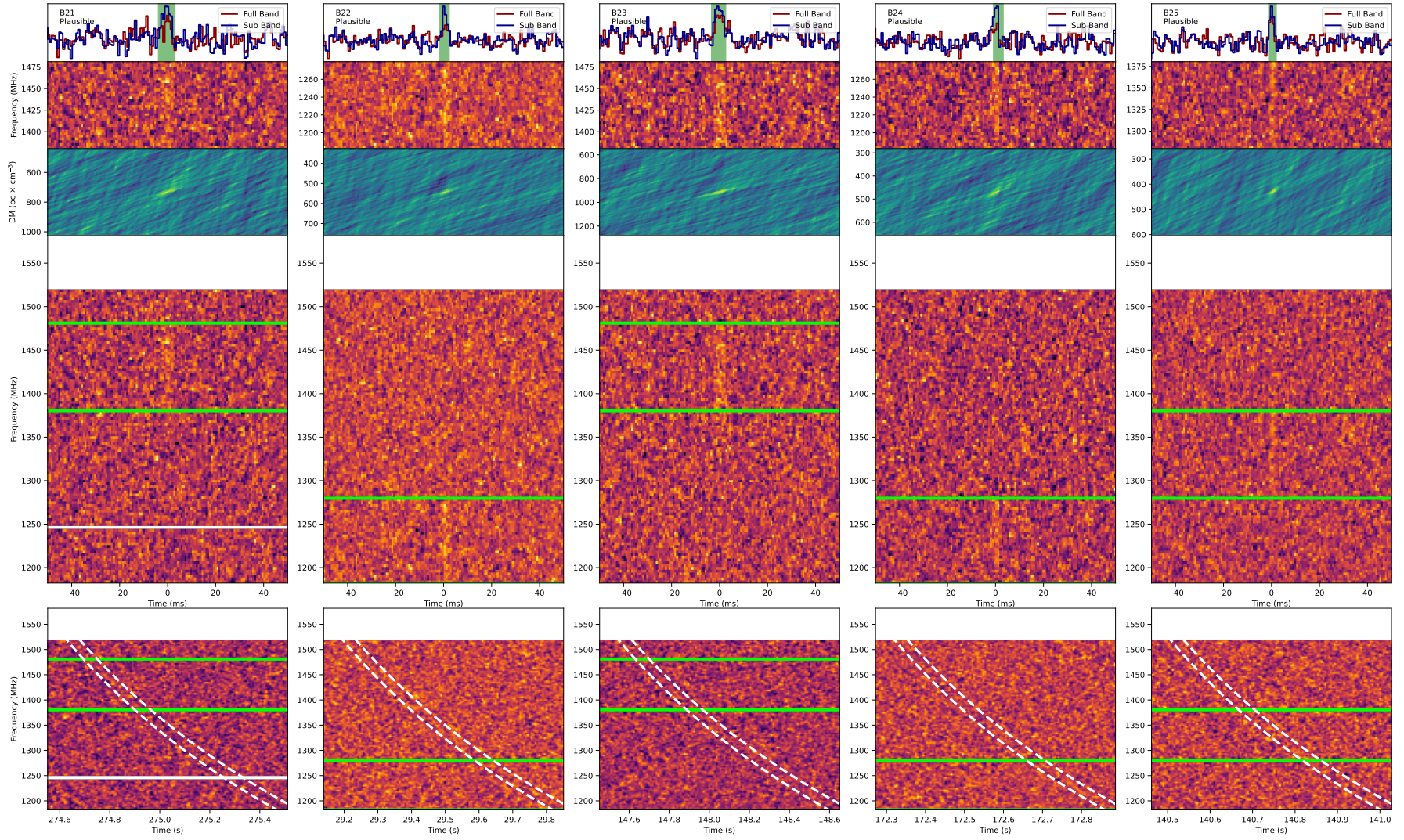


Figure 2.16: The same as Fig. 2.12 for B21-25.

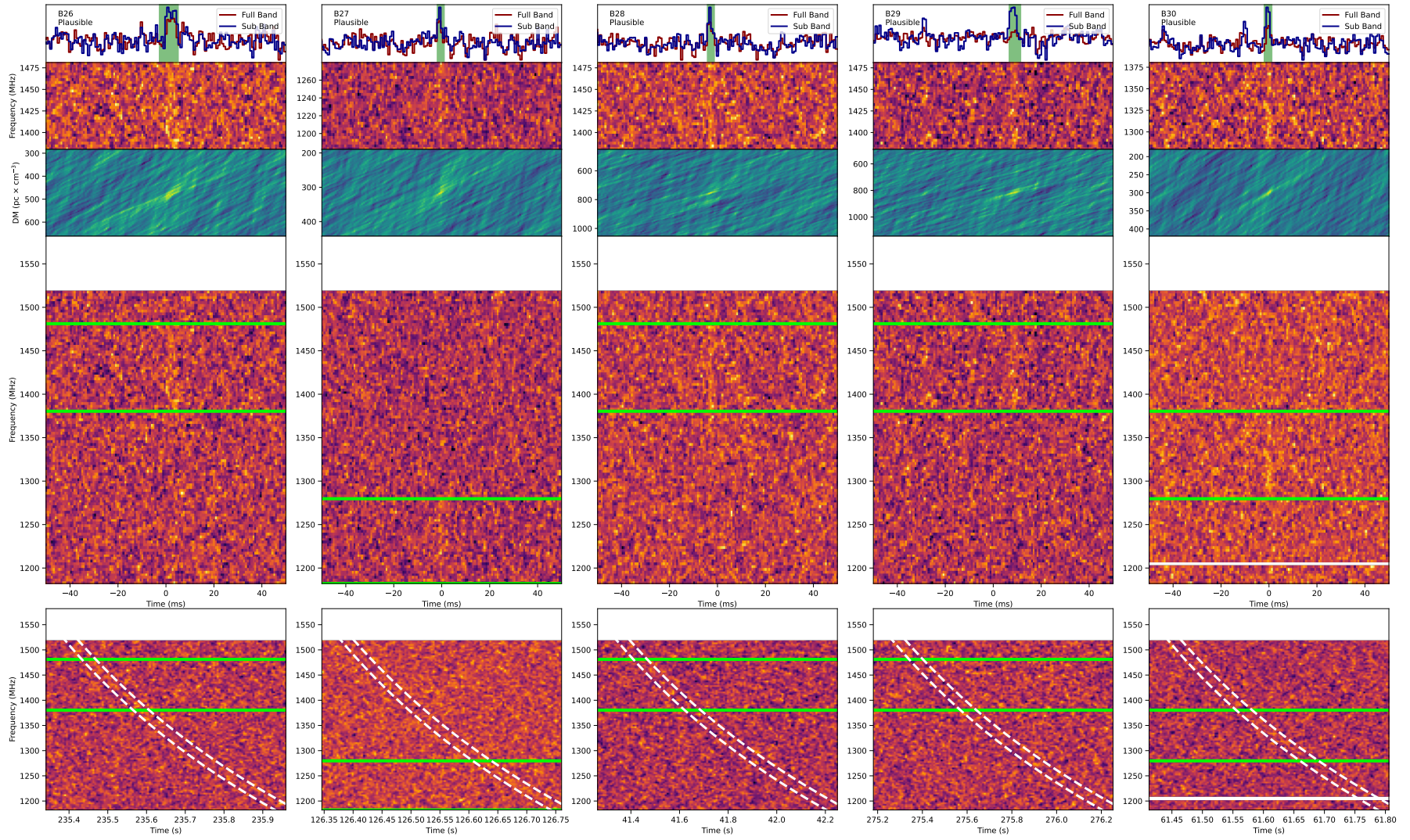


Figure 2.17: The same as Fig. 2.12 for B26-30.

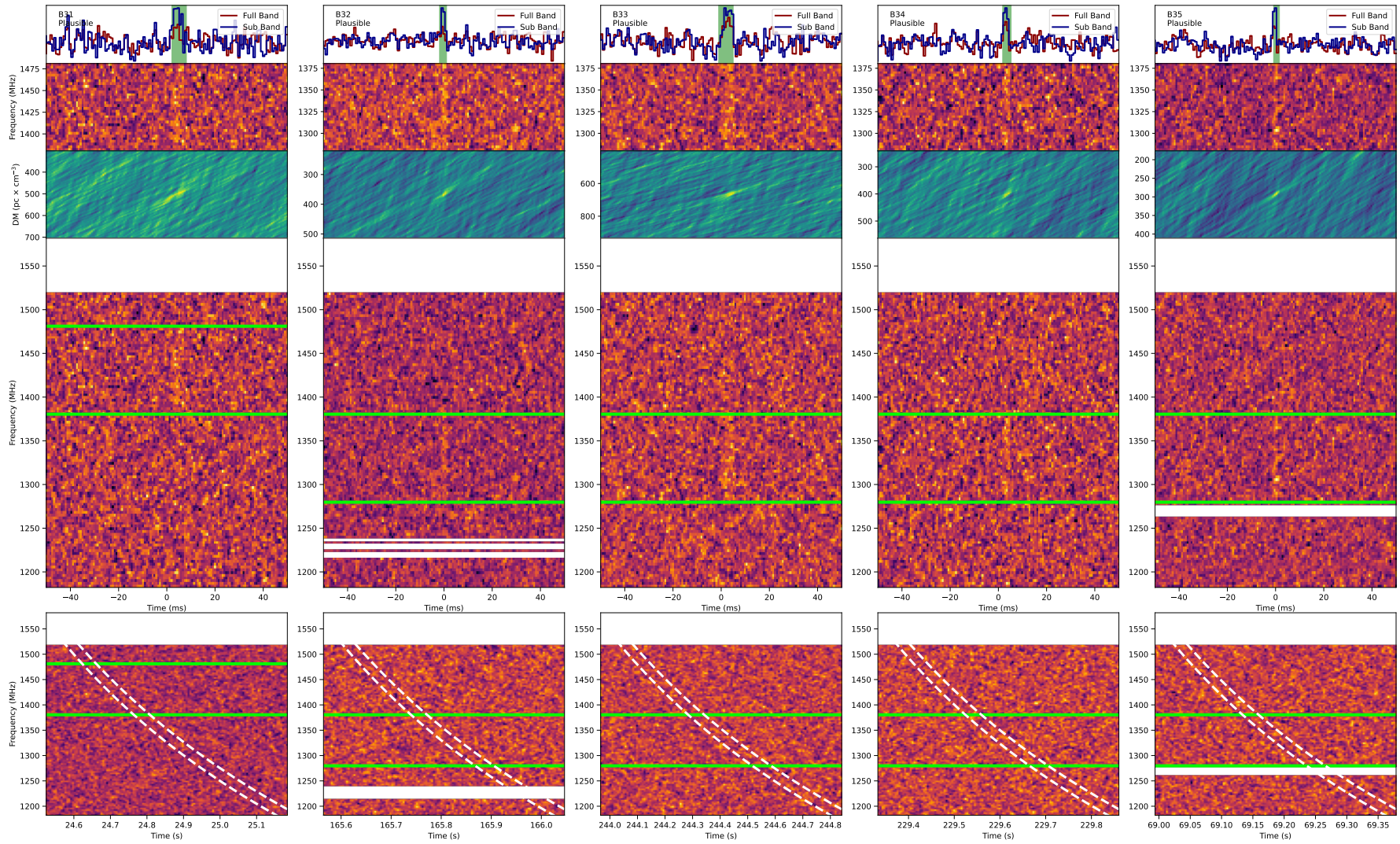


Figure 2.18: The same as Fig. 2.12 for B31-35.

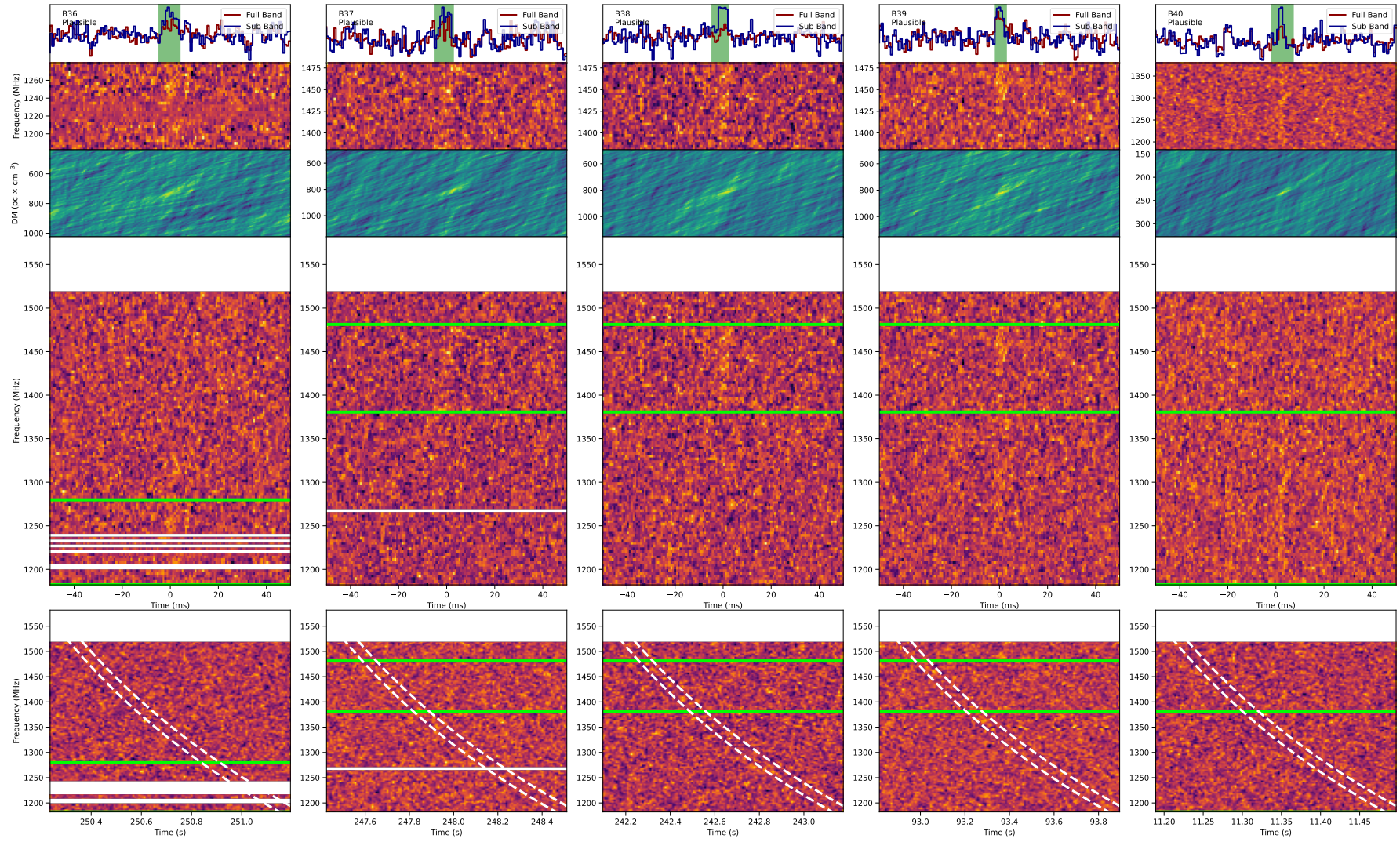


Figure 2.19: The same as Fig. 2.12 for B36-40.

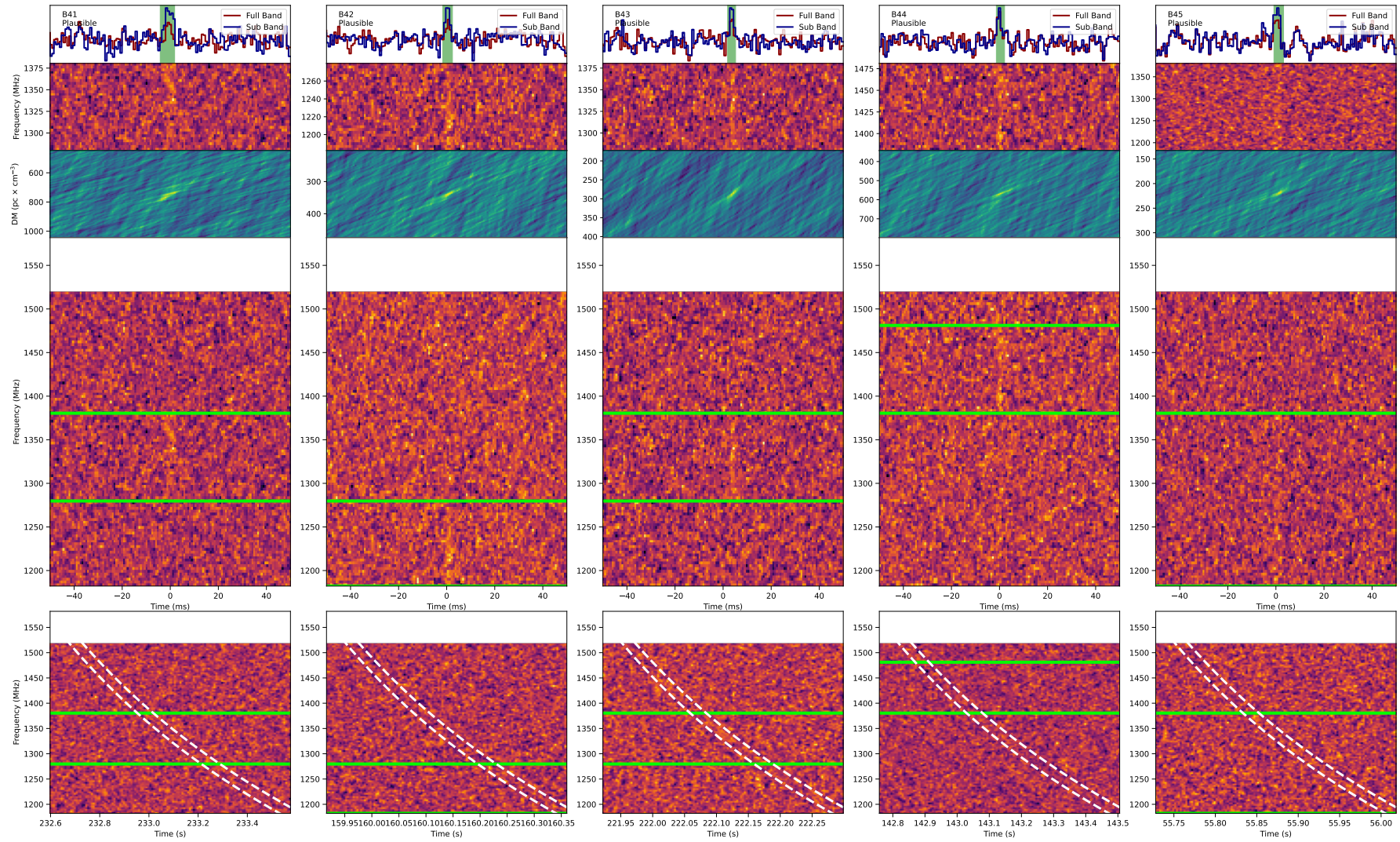


Figure 2.20: The same as Fig. 2.12 for B41-45.

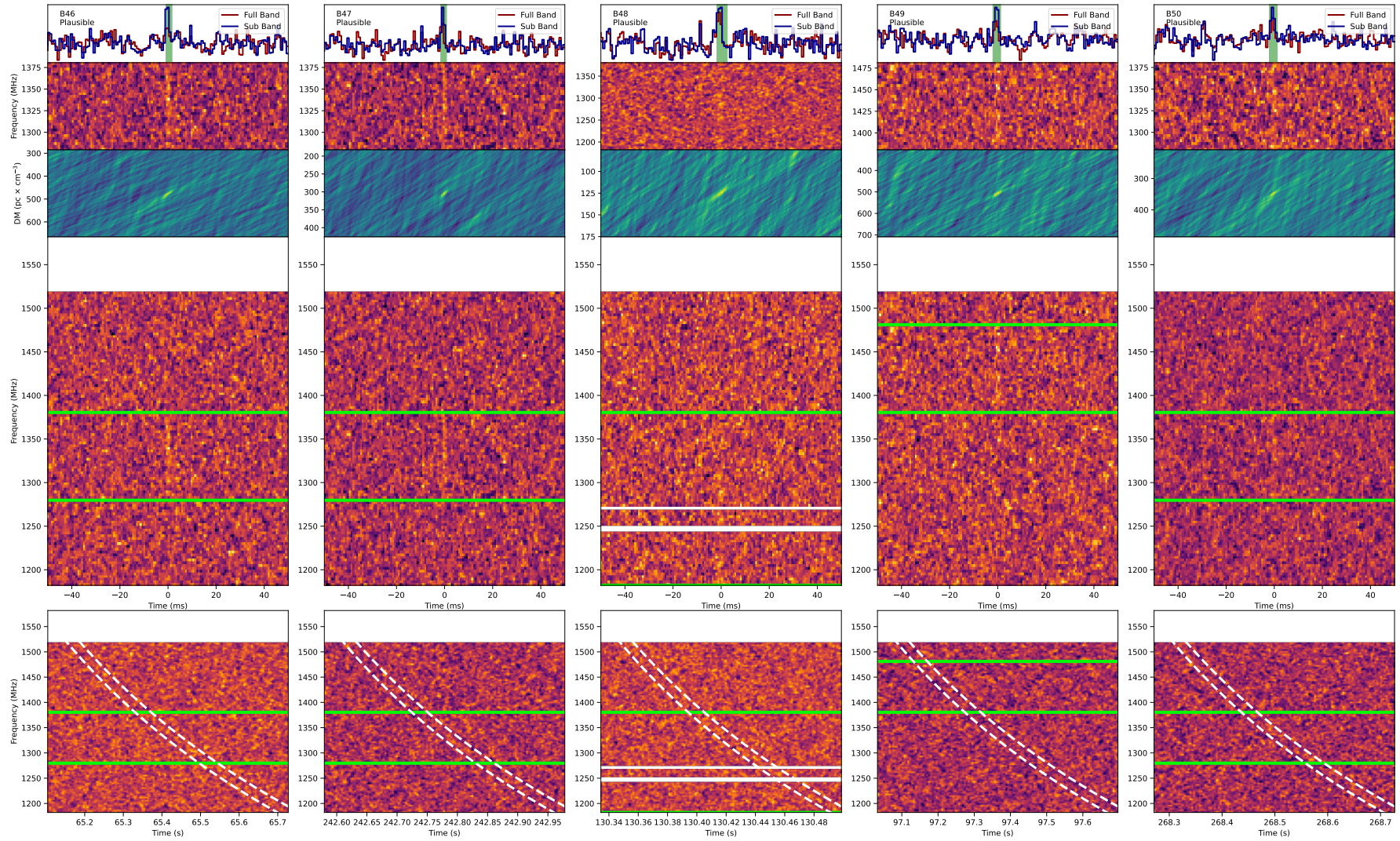


Figure 2.21: The same as Fig. 2.12 for B46-50.

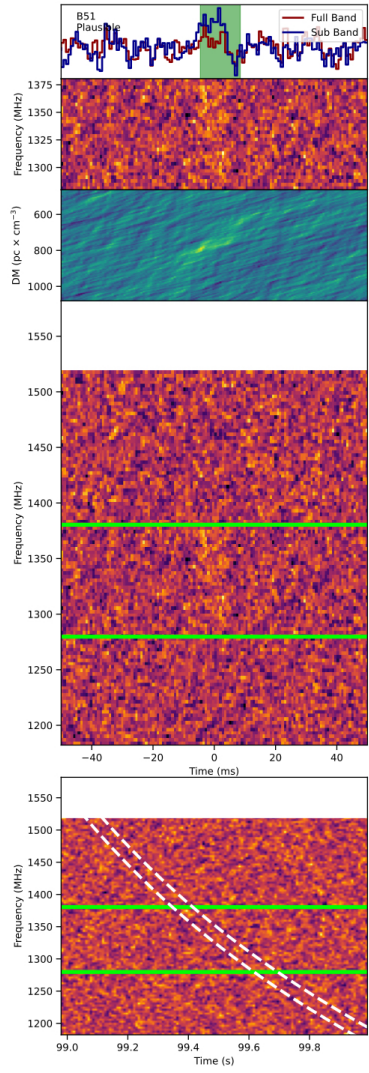


Figure 2.22: The same as Fig. 2.12 for candidate B51.

Instruments for the Detection of the FRBs

This chapter is dedicated to the instruments deployed for the search of FRBs: the radio telescopes. In the first section we will discuss how radio telescopes are generally classified. The second section will introduce the Northern Cross FRB Project, a program devoted to convert an old transit radio interferometer, the Northern Cross (NC, Medicina, Italy) into an FRB machine. The last sections (from Sec. 3.3) will report an original contribution: the first NC FRB campaign on four rFRBs: FRB 20180916B, 20181030A, 20200120E and 20201124A, with the detection of three bursts from FRB 20180916B.

This chapter contains the the results of the following work:

- **M. Trudu** et al. 2022, “*The Northern Cross FRB Project - II. Monitoring of repeating FRB 20180916B, 20181030A, 20200120E, and 20201124A*”, MNRAS, Volume 513, Issue 2, 1858-1866.

3.1 Radio Telescopes

In the previous chapter we described how the EM waves from a source are processed by a radio telescope to make FRB science. The steps described are, in general, the same for any radio telescope deployed. In this section we briefly describe how radio telescopes are classified. More details about radio telescopes can be found e.g. in Wilson, Rohlfs, and Hüttemeister (2013).

Radio telescopes operate in the interval of frequencies from about a few tens of MHz (i.e. wavelengths of hundreds of meters) up to ~ 300 GHz (wavelengths ~ 1 mm). A radio telescope, often simply called antenna, consists in a mirror (the collecting area of which can be designed in various shapes, spherical, parabolic, cylindrical or linear, etc...) which collects the EM radiation. Any antenna has its own *antenna diagram*, which is characterised by a typical a diffraction pattern with multiple maxima. The main maximum indicates the most sensitive direction for the given antenna and it is called *main beam* or *main lobe*. The secondary maxima give sensitivity in other directions, and those are called the “side lobes” of the telescope, and their contribution to the signal should be as low as possible for optimal

reconstruction. The field-of-view (FoV) of the telescope is often considered to be equal to the angular size of the main lobe. The angular resolution $\Delta\theta$ of the main lobe, for a telescope of diameter D , obeys to the well known rule:

$$\Delta\theta \simeq 1.22 \frac{\lambda}{D}, \quad (3.1)$$

where $\lambda = c/\nu$ is the wavelength of the radiation and D the scale-length of the collecting area. The angular resolution $\Delta\theta$ is the minimum angular distance between two points in the sky which can be resolved separately. The *effective area* of the antenna $A_{\text{eff}} \sim D^2$ characterises how much radiation can be collected by the telescope.

3.1.1 Single-dish Telescopes

In many radio telescopes, the collecting area is composed by a single antenna, of various shapes: parabolic reflector, spherical reflector, cylindrical reflector etc... They are commonly called “single-dish”. They work as optical reflectors, by converging the incoming radiation rays in a focal point or focal line or focal plane, where the receiver is placed. Single-dish telescopes are usually quasi-fully steerable, with the Effelsberg (Germany) and Green Bank Telescope (GBT, USA) being the largest (100 m). Due to mechanical limitation, it is quite challenging to make larger aperture single-dishes capable to steer in both the elevation over the horizon and in the azimuth directions. In fact, the two largest telescopes of this category, the Arecibo observatory (Puerto Rico, 305 m in diameter, tragically collapsed in 2020) and the Five hundred meter Aperture Spherical Telescope (FAST, China, 500 m) are *transit telescopes*. Transit telescopes are not fully (or sometimes even partially) steerable. They can observe the sources as they move along the plane of the meridian of the observer. Consequently, their daily observing time is limited to the transit of the source among restricted elevation ranges compared to fully steerable single dishes. See Fig. 3.1 for examples of single-dishes.

3.1.2 Interferometric Arrays

Single-dish telescopes mainly suffer of poor angular resolution, as we see from Eq. 3.1, since, as we mentioned, it is technologically troublesome to make them larger in diameter without losing the telescope mobility. It is possible to overcome this issue by considering more telescopes and the *interferometric technique*.

Let us suppose, for simplicity, to have two radio telescopes (Fig. 3.2). It is then straightforward to generalise to more telescopes. Each pair of telescopes is separated by a vector distance $\vec{b}$ (*baseline*). The main idea behind the interferometry technique is that the signal, in each antenna, will arrive at slightly different times. Both antennas point the same direction, specified by the unit vector $\hat{s}$ and they subtend an angle θ with the baseline vector. If the plane waves from the source arrive at a certain time at the antenna 2, they need to travel an extra amount of time to reach the antenna 1, that is there is a geometric delay $\tau_g = \vec{b} \cdot \hat{s}/c$. The combination of the signals detected by the two receivers, integrated over time, will be proportional to the square of the voltages associated to the two signals, similar to the trace reported in Fig. 3.2. This operation is done in the so-called *correlator*. It can be shown that the angular resolution in this case can still be expressed as Eq. 3.1, but with the absolute value of the baseline length b substituting the dish size D . This means that, in order to have a high angular resolution, as for instance in the case of the localisation of

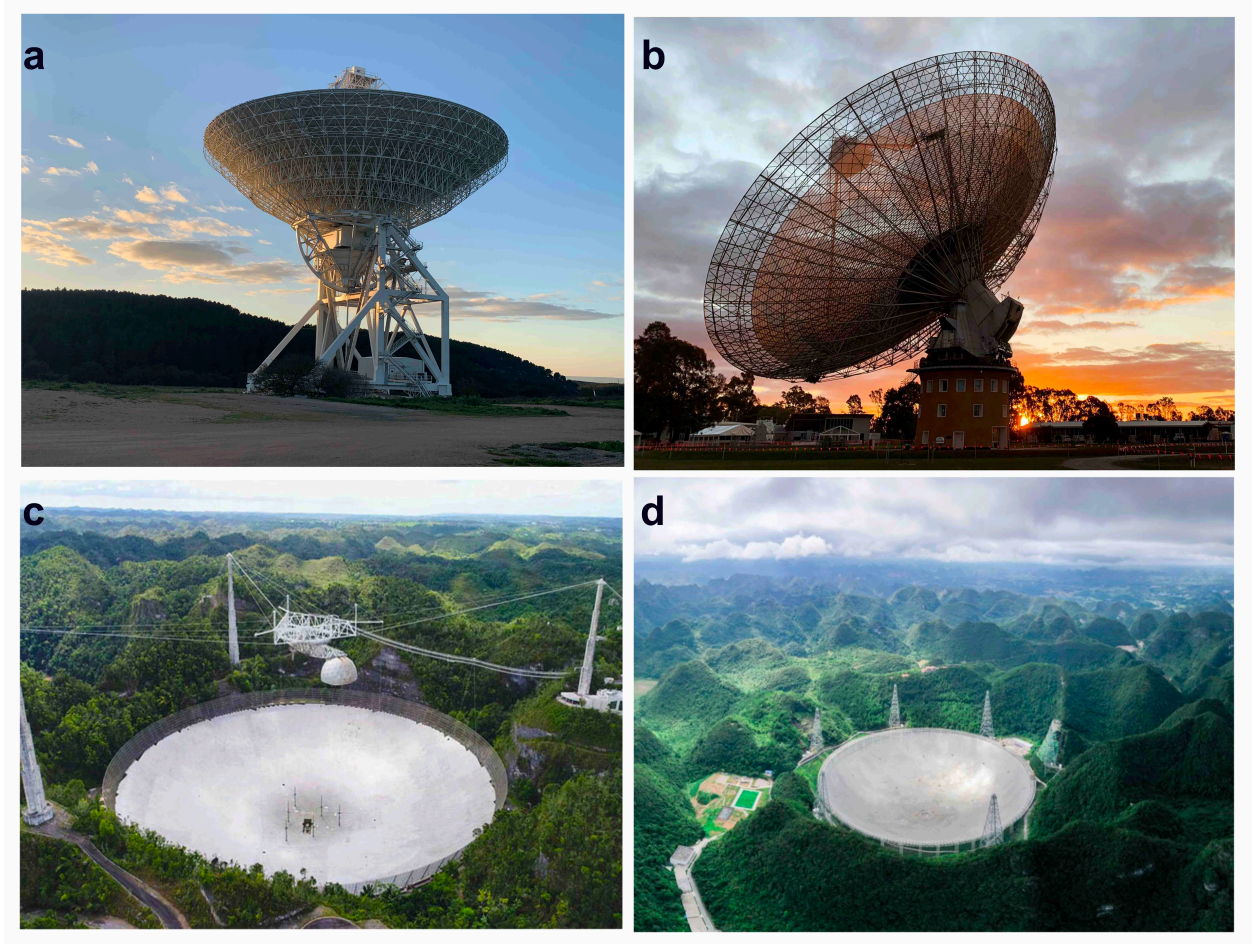


Figure 3.1: Example of single-dish telescopes: the Sardinia Radio Telescope (SRT, a), the Parkes Telescope (b), the Arecibo Observatory (before collapse, c), the Five hundred meter Aperture Spherical Telescope (FAST, d).

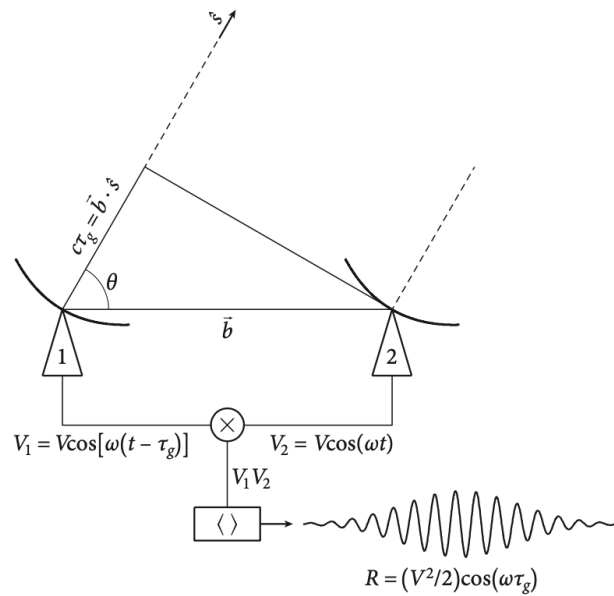


Figure 3.2: A simplified image of a radio interferometer with two elements. See Sec. 3.1.2 for more details. Image from Condon and Ransom (2016).

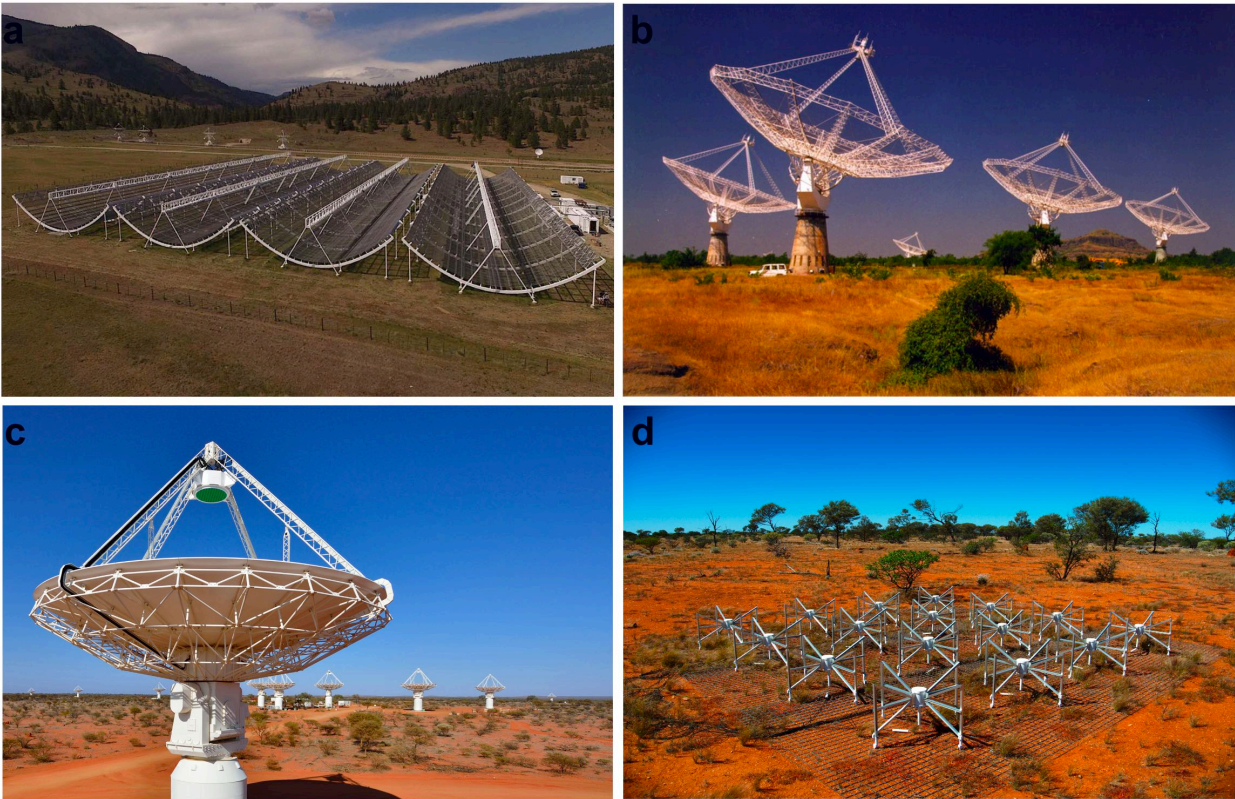


Figure 3.3: Example of arrays of telescopes: CHIME (a), the Giantmetrewave Radio Telescope (GMRT, b), the Australian Square Kilometre Array Pathfinder (ASKAP, c), the Murchison Widefield Array (MWA, d).

an FRB, very long baselines are required. Figure 3.3 shows some example of interferometric arrays.

The inteferometric technique can be performed also with a group of large single-dish telescopes far away from each other. This technique is called Very Long Baseline Interferometry (VLBI). In fact FRBs like FRB 20121102 (Marcote et al., 2017), FRB 20180916B (Marcote et al., 2020), FRB 20200120E (Kirsten et al., 2022), FRB 20201124A (Nimmo et al., 2022), have been localised with a milli-arcsecond precision thanks to the European VLBI Network (EVN), a network of radio telescopes located primarily in Europe with the addition of some Asian, South-African and South American telescopes¹.

3.2 The Northern Cross FRB Project

This section serves as an introduction to the Northern Cross FRB Project (NC-FRB). The NC-FRB started in 2019, with the aim to refurbish the NC telescope and make that a modern radio transient facility for pulsars, RRATs, magnetars and FRBs, as well as for monitoring and tracking space debris.

3.2.1 Brief History

The idea of building a radio telescope in the countryside of Medicina (Bologna) was carried on primarily by the physicists A. Braccesi and M. Ceccarelli (Braccesi and Ceccarelli, 1962). The NC telescope design was based on the Mills Cross Telescope, the first T-shaped radio telescope, built by B. Mills (Mills et al., 1958) in New South Wales (Australia) in 1954. The NC construction started in 1960 and finished in 1967. The main purpose of the telescope was to make surveys of the sky, and this produced the notable catalogues from Colla et al. (1970), Ficarra, Grueff, and Tomassetti (1997) and Pedani and Grueff (1999). The first works with the NC in the context of pulsar astronomy are from D’Amico et al., 1996, where they report the long term timing of a sample of pulsars, coordinated with the Compton Gamma-ray Observatory Mission. Also, a search for rapidly rotating pulsars was performed in the mid Nineties and led to the discovery of one millisecond pulsar (D’Amico, 2000). The NC underwent a refurbishment in 2019 to make it capable to observe FRBs, and space debris. The system and its survey capabilities are described in Locatelli et al. (2020), hereafter Paper I.

3.2.2 Instrument Overview

The NC radio telescope is a transit telescope which operates at 408 MHz (P-band) with an observational bandwidth of 16 MHz. It is a T-shaped interferometer (see Fig. 3.4 a) with the two arms aligned along the North-South (NS) and East-West (EW) directions. The EW is currently not in use and its renovation will be part of one of the financed programs by the Italian Ministry of Education and Research. To date, only the NS arm is in use.

The NS arm possesses a total of 64 reflective parabolic cylinders of 7.5×23.5 m each (see Fig. 3.4 b), for a total collective area of 11280 m^2 and an effective area of 8000 m^2 (Bolli et al., 2008). Each cylinder illuminates four groups of 16 dipoles each, for a total of 64 dipoles. Signals from each of the 16 dipoles are combined together analogically and fed to a single receiver. Cylinders are spaced 10 m apart. The total NS arm is long 640 m.

¹<https://www.evlbi.org/>.

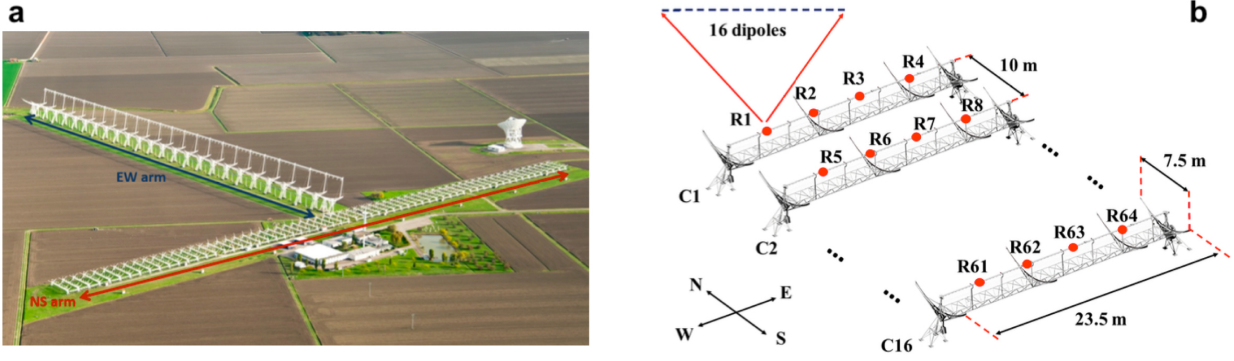


Figure 3.4: (Panel a) areal view of the NC telescope with the NS and EW arms highlighted; (panel b) scheme showing 16 cylinders of the NS arm, where the red points indicate the position of the receivers. Images from (Locatelli et al., 2020).

3.3 The NC monitoring of FRB 20180916B, 20181030A, 20200120E and 20201124A (Original Contribution)

In the following sections we report on the results of a nineteen-month FRB (from January 2020 until August 2021) observational campaign carried out with the NS arm of the NC radio telescope in which we monitored four repeating sources: FRB 20180916B, 20181030A, 20200120E and 20201124A. We present the current state of the instrument and the detection and characterisation of three bursts from FRB 20180916B. We show that, given our observing time, our detections are consistent with the event number we expect from the known burst rate (2.7 ± 1.9 above a $S/N = 10$, 38 Jy ms detection threshold) in the 5.2 day active window of the source, further confirming the source periodicity. We detect no bursts from the other sources. We turn this result into a 95% confidence level lower limit on the slope of the differential fluence distribution α to be $\alpha > 2.1$ and $\alpha > 2.2$ for FRB 20181030A and FRB 20200120E respectively. Given the known rate for FRB 20201124A, we expect 1.0 ± 1.1 bursts from our campaign, also consistent with our non-detection.

3.4 System description

3.4.1 Data Acquisition System

Until March 21st 2021, only six cylinders out of 64 were used, for a total of 24 receivers, whereas, afterwards, eight cylinders were equipped and used, for a total of 32 receivers.

The acquisition system, which broadly follows the steps described in Sec. 2.1, is based on the Analogue Digital Unit board (ADU, see e.g. Paper I; Naldi et al. 2018; Comoretto et al. 2017 for a more detailed description of the digital backend). Signals from the receivers are digitised, channelised and combined into a single beam. The beam-formed data are written to disk as 16 bit SIGPROC filterbank files. In a step forward with respect to the system described in Paper I, where the frequency channel resolution was 781 kHz, we have implemented a second channelisation stage with a widowed FFT, which allowed to have a finer frequency resolution of 14.468 kHz among 1024 spectral channel, with a 138.24 μ s time resolution.

During the observing campaign we used the eight-cylinder system to observe the transit of two bright sources, Taurus A and Virgo A, for 2 hours each, in order to further charac-

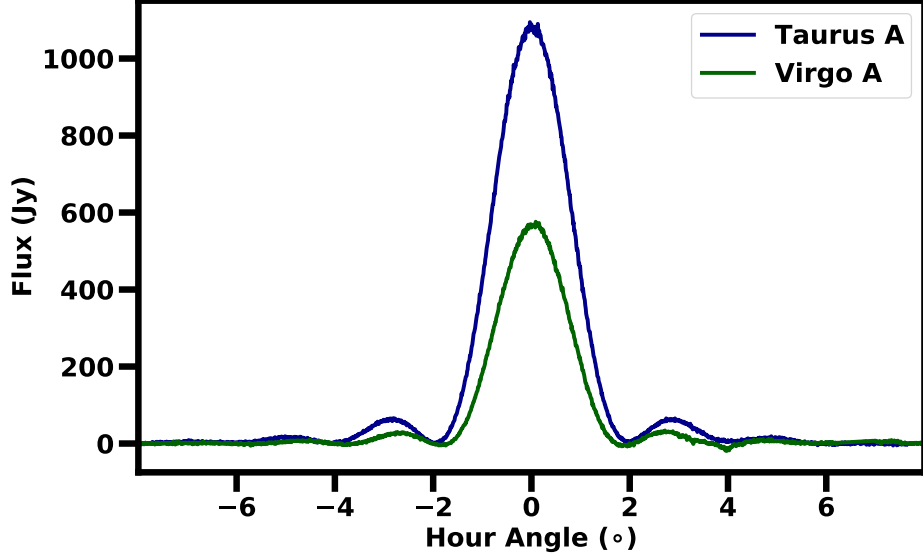


Figure 3.5: Calibrated drift scans of the astronomical sources, Taurus A and Virgo A, used for the SEFD estimation, observed with the eight-cylinders array beam, referred to the channel corresponding at the central frequency of 408.45 MHz. The profile clearly shows the main and the first lobes of the array beam.

Table 3.1: Astronomical sources used as calibrators. SEFDs are estimated for groups of 16 dipoles (i.e. one receiver). The SEFD for six and eight cylinders can be obtained by multiplying for the corresponding number of receivers, 24 and 32 respectively.

Source	Sky Position (RA J2000, DEC J2000)	Starting Time UT	SEFD (Jy)
Taurus A	05 ^h 34 ^m 31.940 ^s , +22°00′52.20″	2021/04/13 14:21:03	9000 ± 400
Virgo A	12 ^h 30 ^m 49.423 ^s , +12°23′28.05″	2021/04/01 22:03:02	7800 ± 180

terise the System Equivalent Flux Density (SEFD), following up on the estimates derived in Paper I from observations of the PSR B0329+54 pulsar. Figure 3.5 shows the corresponding transit observations, where the telescope was steered towards the corresponding declination of each source. We perform a standard on-off observation, where we estimate the background contribution as the average of the power away from source, i.e. for hour angles $> |6^\circ|$, and subtract it from the observed power when the source is within the main beam. We then fit a Gaussian model to the profile full width at half maximum (FWHM) for 21 frequency channels equally spaced across the 16 MHz bandwidth. Taurus A and Virgo A are assumed to be 1080 Jy and 569 Jy at 408 MHz respectively (Perley and Butler, 2017), and the best fit to the curve peak provides the conversion from counts to Jy for each channel. The SEFD is derived from the rms of the calibrated power away from sources, i.e. for hour angle $> |6^\circ|$. The SEFD is found to vary up to 20% across the bandwidth, a negligible variation for the purpose of the current analysis. We eventually average the SEFD estimates to obtain a band-averaged value (Tab. 3.1).

We note a slight dependence of the SEFD with the Galactic latitude, varying by $\sim 14\%$ from the Galactic plane (Taurus A is at a $\sim -5^\circ$ Galactic latitude) to high Galactic latitudes (Virgo A is at a $\sim +74^\circ$ Galactic latitude). This dependence is qualitatively expected as the sky temperature contribution to the SEFD increases towards the plane. At the same time,

our results indicate that the sky temperature contribution to the SEFD is minor. For the purpose of this work we will adopt the same SEFD* estimate for all FRB sources, obtained by averaging the Taurus A and Virgo A values:

$$\text{SEFD}^* = 8400 \pm 420 \text{ Jy} . \quad (3.2)$$

3.4.2 Single Pulse Search Pipeline

The search for FRB candidates is currently performed through an adaptation of the SPANDAK pipeline (Gajjar et al., 2020). The pipeline is a python-based wrapper of Heimdall which integrates the routine `rfind` from PRESTO (Ransom, Eikenberry, and Middleditch, 2002) to prepare the RFI mask, which is then used by Heimdall (Barsdell et al., 2012) in order to flag out the noisiest frequency channels. The data are then searched by SPANDAK through Heimdall across a DM range from 0 to 1000 pc cm⁻³ with a S/N loss tolerance in each DM trial of 10% and, finally, the dedispersed time series have been convolved with a maximum boxcar of 1024 samples.

As similarly as done in Chap. 2.4.3, the candidates found are then further selected by SPANDAK, exploiting `frb_detector.py`, according to their S/N , DM, width of the burst Δt , maximum number N_w of allowed candidates found within a time window w centred at the time of the candidate and the minimum number N_m of distinct boxcar/DM trials (members) clustered into a candidate. Candidates which agree with the following criteria are classified as plausible FRB candidates:

$$\begin{aligned} S/N &\geq 10 ; \\ \text{DM} &\geq 10 \text{ pc cm}^{-3} ; \\ \Delta t &\leq 141.6 \text{ ms} ; \\ N_{w=4 \text{ s}} &\leq 2 ; \\ N_m &\geq 10 . \end{aligned} \quad (3.3)$$

Filtered candidates are then validated by the artificial neural network classifier FETCH (Agarwal et al., 2020) and, eventually, manually inspected.

3.5 Selected Targets

We report the results of the observational campaign conducted between the 16th of January 2020 and the 29th of August 2021 for the following four repeating FRB sources: FRB 20180916B, FRB 20181030A, FRB 20200120E, FRB 20201124A. These sources were selected for their proximity, as initially suggested by their low DM values and later confirmed by their localisation. This makes them favourable targets both for our new system and for the multi-wavelength campaign which was led in the radio band, either exclusively or coupled with the SRT, by the NC (see, e.g. Tavani et al., 2021a; Tavani et al., 2020b; Pilia et al., 2020).

The whole NC campaign is summarised in Fig. 4.2, including all the observations performed for the monitored sources at the various epochs. We highlight the time when the transition between the six-cylinders system and the eight-cylinders system occurred. In the following sections we will describe the targets in more detail.

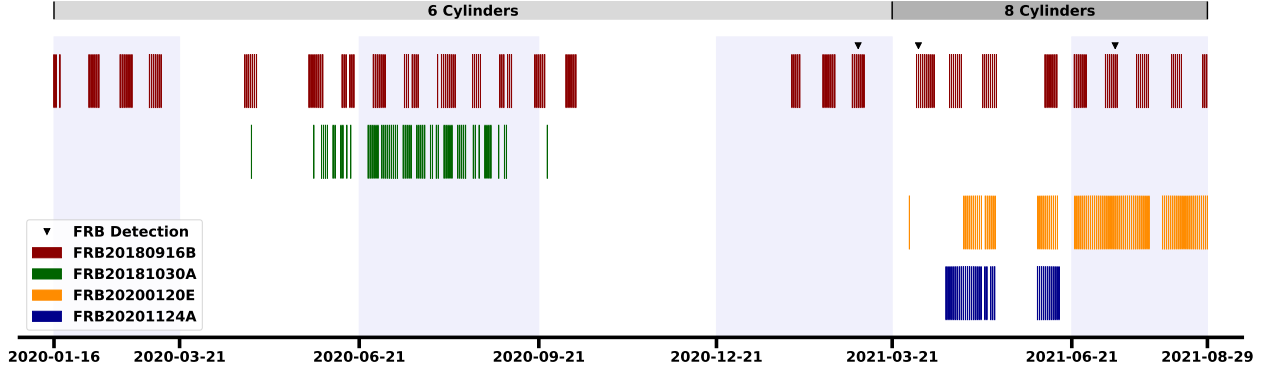


Figure 3.6: Observational campaign of the NC telescope. Coloured bars represent observations performed for each FRB source as a function of the day of the year. Black triangles indicate days when FRB were detected. Seasons of the year have been depicted as alternated white and lavender rectangles, to help the eye. The top grey and dark grey bars represent, respectively, the time in which the six-cylinders and eight-cylinders system were used during the campaign.

3.5.1 FRB 20180916B

FRB 20180916B (see Sec.1.2.12 for more information about the source) is our main target and was observed for a total of ~ 180 hours throughout the campaign. Starting in January 2020, when its periodic activity was announced (Chime/FRB Collaboration et al., 2020), the NC observed FRB 20180916B regularly during its active cycles. FRB 20180916B has a periodic activity of ~ 16 days with an active window of ~ 5 days and we observed the source for about seven days each cycle, beginning one day before the period (predicted in the CHIME/FRB bandwidth) in order to match the multi-wavelength campaign from the Swift and AGILE satellites, trying to catch earlier emission (Casentini et al., 2020; Tavani et al., 2021a; Verrecchia et al., 2021). The primary aim of these observations was indeed to find theoretically predicted multi-wavelength counterparts (Lyubarsky, 2014; Beloborodov, 2017b; Kumar, Lu, and Bhattacharya, 2017; Ghisellini and Locatelli, 2018; Metzger, Margalit, and Sironi, 2019; Lu, Kumar, and Zhang, 2020b; Lyutikov and Popov, 2020), looking for time coincidences with other instruments (see Nicastro et al., 2021, for an updated review).

3.5.2 FRB 20181030A

FRB 20181030A is the fourth known repeater, with two bursts detected by CHIME/FRB in October 2018 (CHIME/FRB Collaboration et al., 2019b) and seven new bursts detected in January 2020. It has a $DM \sim 103 \text{ pc cm}^{-3}$ and a maximum estimated redshift of $z = 0.05$. The star-forming spiral galaxy NGC 3252 ($z \sim 0.004$) has been identified as its most auspicious host among seven plausible galaxies within the 90% confidence localisation region (Bhardwaj et al., 2021).

Due to its small DM value, with an associated distance of ~ 20 Mpc, FRB 20181030A has been monitored, on an approximately daily basis, from April 2020 until September 2020, for a total of 93 hours, as an interesting target for multi-wavelength observations despite the initial lack of localisation. This source, however, has shown very little activity over the last years, compared to FRB 20180916B: only nine bursts were detected by CHIME since its discovery, with a fluence smaller than 10 Jy ms.

3.5.3 FRB 20200120E

FRB 20200120E is a repeater with $DM \sim 88 \text{ pc cm}^{-3}$ (Bhardwaj et al., 2021b), initially localised in the outskirts of M81, a spiral galaxy with a distance of $\sim 3.6 \text{ Mpc}$ (Freedman et al., 1994) and afterwards precisely localised in a globular cluster within M81 with the detection of five bursts from the source at 1.4 GHz (L-band) by the EVN (Kirsten et al., 2022). Thanks to the relative proximity of the source and also thanks to its high Galactic latitude ($\sim 41.2^\circ$), which makes the scattering broadening due to the Milky Way interstellar medium negligible, an ultra-high-time resolution analysis of the five bursts detected by Kirsten et al. (2022) has been performed, showing that this source can produce nanosecond duration isolated bursts with 10^{41} K brightness temperature (Nimmo et al., 2021a), similar to the Crab Giant pulses (Hankins et al., 2003). This unprecedented finding marked a bridge between young Galactic pulsars and magnetars and the more distant FRBs in terms of burst durations and luminosities (see in particular Fig. 3 from Nimmo et al., 2021a).

This target was included in the selection in light of its being the closest known repeater so far. Analogously to FRB 20181030A we monitored this source about once a day from March 2021 to the last day of the campaign, for a total observing time of ~ 109 hours.

3.5.4 FRB 20201124A

FRB 20201124A is a repeater with $DM \sim 410 \text{ pc cm}^{-3}$, discovered by CHIME/FRB in November 2020. It had a very active phase between March and May 2021 (Lanman et al., 2022; CHIME/FRB Collaboration, 2021), with a plethora of follow-up detections by other radio telescopes (Kumar et al., 2021b; Marcote et al., 2021; Xu et al., 2021; Law et al., 2021; Wharton et al., 2021) at both P and L bands, with an initial localisation of the source by ASKAP (Day et al., 2021), FAST (Xu et al., 2021), uGMRT (Wharton et al., 2021) and VLA (Law et al., 2021) and further refined, with a milliarcsecond precision, by the EVN (Nimmo et al., 2022). It was localised in a nearby ($z \sim 0.098$) (Fong et al., 2021) galaxy with a high star formation rate which suggests a new-born magnetar as the most likely progenitor (Piro et al., 2021). We monitored this source daily from April 2021 to June 2021 for a total observing time of 68 hours.

3.6 Bursts Detected

We report the detection of three bursts from FRB 20180916B: B1, B2 and B3, from now on. These bursts happened on March 3rd 2021, April 3rd 2021 and July 13th 2021, respectively. Tab. 3.2 reports the observed properties of the detected bursts. Fig. 3.7 shows the dedispersed waterfall plots of B1, B2 and B3, obtained with the fit-optimised DM reported in Tab. 3.2.

Table 3.2: Properties of the detected bursts of FRB 20180916B from the NC campaign. The second column reports the percentage of channels excised as RFI; the third, the fourth and the fifth columns report the barycentric (∞ MHz) time of arrival of the bursts as MJD, UT and phase of the activity period of FRB 20180916B; the sixth column reports the fit-optimised DM; the seventh column the S/N ; the eighth column reports the FWHM burst duration in ms; the ninth column reports the scattering time computed with respect to the reference frequency of 408 MHz; the tenth and eleventh columns report respectively the flux densities and the fluences of the bursts.

	ξ (%)	TOA (MJD)	TOA (UT)	ϕ	DM (pc cm ⁻³)	S/N	Δt (ms)	τ_s (ms)	S (Jy)	F (Jy ms)
B1	2	59276.5954859605(4)	2021-03-03 14:17:29.987(1)	0.554 ± 0.008	$349.28^{+0.25}_{-0.26}$	14.5	$4.76^{+0.57}_{-0.63}$	/	20 ± 2	96 ± 14
B2	12	59307.5148011862(7)	2021-04-03 12:21:18.822(4)	0.447 ± 0.007	$349.57^{+0.36}_{-0.36}$	21.7	$5.95^{+0.75}_{-0.68}$	< 3.6	22 ± 3	135 ± 19
B3	8	59408.2528584486(4)	2021-07-13 06:04:06.970(6)	0.616 ± 0.009	$349.64^{+0.35}_{-0.37}$	12.5	$4.37^{+0.45}_{-0.45}$	/	16 ± 1	71 ± 8

3.6.1 Burst Characterisation

The properties of the detected bursts, that is their TOA, the width Δt , the best DM and the scattering time τ_s have been computed by making a fit of the spectro-temporal data array. We use, as a template for the burst in the time domain, a Gaussian function convolved with an exponential decay function (McKinnon, 2014) and a Gaussian function for the burst in the frequency domain. The fit procedure has been performed using the software package `burstfit`. A detailed description of this package can be found in Aggarwal et al. (2021).

The peak flux density S of the incoming radiation from the source is computed by using a modified version of the standard radiometer equation for single pulses (Lorimer and Kramer, 2005):

$$S = S/N \times \frac{\text{SEFD}^*}{A\sqrt{N_p N_c (1 - \xi) d\nu \Delta t}} \zeta(\text{TOA}) . \quad (3.4)$$

Here S/N is the integrated signal-to-noise ratio of the frequency averaged time series, $A = 24$ or 32 is a geometric factor which takes into account the ratio between the collecting area of the six or eight cylinders system and one receiver, $N_p = 1$ is the number of polarisations, $N_c = 1024$ is the number of spectral channels of the observation, ξ is the fraction of channels excised as RFI and $d\nu$ is the channel width. The multiplicative factor $\zeta(\text{TOA})$ takes into account the primary beam attenuation at the burst TOA.

The estimated fluences F of the bursts were calculated as the product between the flux density S and the duration of the burst Δt .

3.6.2 Bursts Properties

The top panels of Fig. 3.7 show the frequency averaged time series of B1, B2 and B3. We obtain a significant measurement for the scattering time only for B2, with a value of 3.6 ms at 408 MHz. This would correspond to ~ 0.8 ms at 600 MHz, consistent with previous scattering time measurements reported for this source (CHIME/FRB Collaboration et al., 2019b). However, we consider this value as an upper limit as Marcote et al. (2020) and Pastor-Marazuela et al. (2021) placed a tighter constraint on the scattering time scale of the order of $3 \mu\text{s}$ at 1.7 GHz, similar to the NE2001 (Cordes and Lazio, 2002) prediction of $2 \mu\text{s}$. Our estimate would correspond to $10 \mu\text{s}$ at 1.7 GHz. Hence, we conclude that this apparent scattering tail, as showed in the model for B2 in Fig. 3.7, could be originated by the presence of not resolvable sub-bursts (CHIME/FRB Collaboration et al., 2019b).

None of the three detected burst show peculiar spectro-temporal features (bottom panels of Fig. 3.7), that is the typical downward drift of the signal in the time-frequency plane (the “sad trombone effect” mentioned in Sec. 1.2.11) often reported for repeater sources (Chime/FRB Collaboration et al., 2020; Hessels et al., 2019; Pleunis et al., 2021), as can be seen from the dynamic spectra in Fig. 3.7.

Figure 3.8 shows the span of our observations and the occurrence of B1, B2 and B3 as a function of the relative phase ϕ , during the activity cycles of FRB 20180916B. The phases are obtained folding the data at the nominal period of 16.33 days taking a starting epoch $T_0 = 58369.40$ MJD (corresponding to Cycle 1), such that $\phi = 0.5$ corresponds to the peak of the activity of the source (see Pleunis et al., 2021, for further details).

The obtained phases for B1, B2 and B3 are reported in Tab. 3.2. From Fig. 3.8 we see that the three burst are consistently located within the predicted activity window of 5.2 days from CHIME/FRB, since our observational bandwidth overlaps with theirs (see again Pleunis

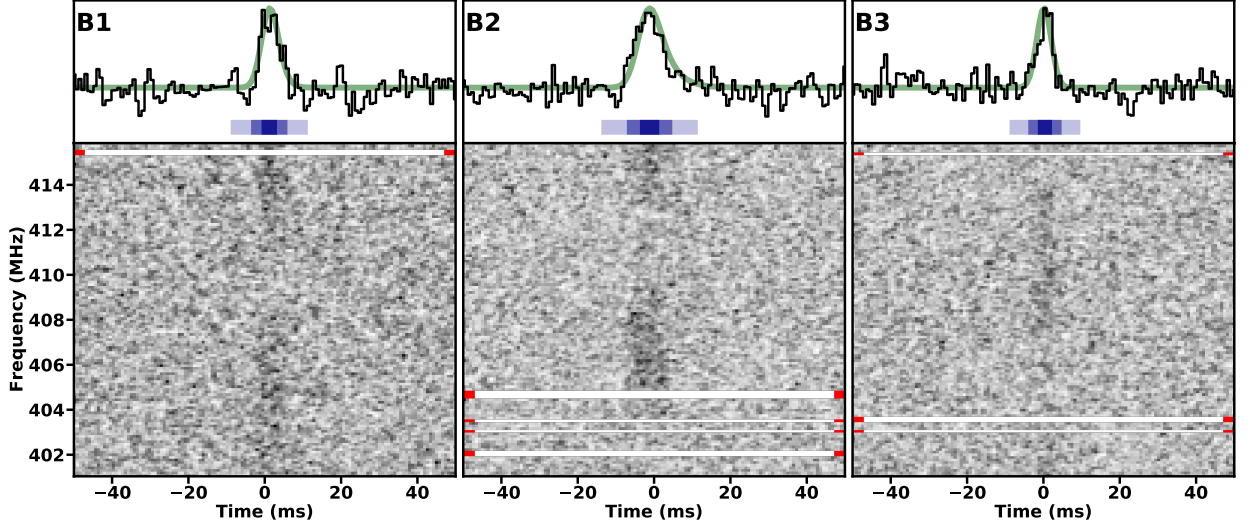


Figure 3.7: Bursts observed from FRB 20180916B (B1, B2 and B3) during the NC observational campaign. Bottom-(left, centre and right) panels represent the dynamic spectrum of the signal, whereas the top-(left, centre and right) are the frequency averaged time series (black curves) and the best-fit model (green curves) of the three bursts. For each burst the 2σ , FWHM and 10σ widths are displayed as blue rectangles. The bursts are, from left to right, ordered by time and each of them has been dedispersed according to the obtained best DM (see Tab. 3.2). For a better display, data are down-sampled to have 128 frequency channels with a 0.116 MHz width each and 128 time bins with size of 0.78 ms. Horizontal white rows (highlighted with red ticks) are flagged channels due to RFI.

et al., 2021, Fig. 9). We do not report any detection from outside its window of activity (Fig. 3.8), consistently with the observed chromatic activity, as discussed in Secs. 1.2.13.

3.6.3 Rate Estimation and Comparison with CHIME/FRB

We estimate the number of expected bursts at our facility for the monitored sources, making a comparison with the detection rates reported by CHIME/FRB, due to the partially overlapping observational bandwidths. Let us assume that the differential number of bursts dN , for a facility x which operates at the central frequency ν_c^x , with fluence (or equivalently flux density for a 1 ms burst), within the interval $(F, F + dF)$ follows a power law of the kind:

$$\frac{dN^x}{dF} = K \left(\frac{\nu_c^x}{\nu_{\text{ref}}} \right)^{-\beta} \left(\frac{F}{F_{\text{ref}}} \right)^{-\alpha}. \quad (3.5)$$

Here F_{ref} , ν_{ref} are respectively a reference fluence and a reference frequency; K corresponds to dN^x/dF at $\nu = \nu_{\text{ref}}$ and $F = F_{\text{ref}}$; $\beta = 1.5 \pm 0.3$ (Macquart et al., 2019) is the spectral index; α is the slope of the differential fluence distribution (see The CHIME/FRB Collaboration et al., 2021, §6.2)². The value of α appears to be different for each source, although the possibility of a universal parameter for at least the class of repeaters is still open (see e.g. Marthi et al., 2022, for a discussion). In the case of FRB 20180916B, the value is $\alpha = 2.3 \pm 0.4$

²Here we consider a different convention for the slope α with respect to the one used in The CHIME/FRB Collaboration et al. (2021). Our α refers to the differential fluence distribution, whereas they use the cumulative fluence distribution. The values of α reported in the reference, to be in accord with our convention, should be read as $-\alpha + 1$.

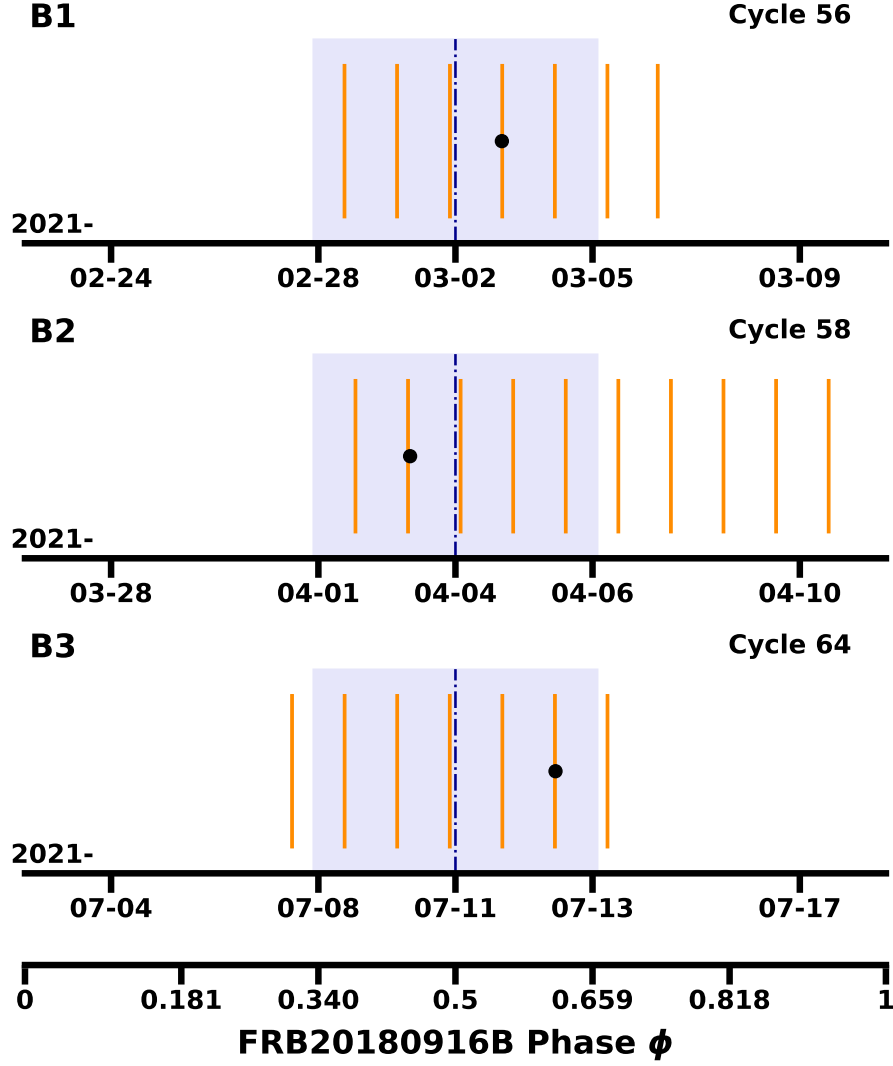


Figure 3.8: Bursts B1, B2 and B3 as a function of the periodicity phase ϕ . Orange bars show the NC observations during the source activity cycles (lavender rectangle). Cycle 1 corresponds to the first burst detection (Chime/FRB Collaboration et al., 2020), with a starting epoch $T_0 = 58369.40$ MJD and $\phi = 0.5$ to be the centre of the activity window. Our detections (black circles) happened during Cycles 56, 58 and 64 respectively.

(Chime/FRB Collaboration et al., 2020), Assuming that an FRB source is observed for an average observing time δt_{obs}^x , we can evaluate the differential burst rate dR^x/dF from Eq. 3.5 as:

$$\frac{dR^x}{dF} = \frac{d^2 N^x}{dF dt} = \frac{K}{\delta t_{\text{obs}}^x} \left(\frac{\nu_c^x}{\nu_{\text{ref}}} \right)^{-\beta} \left(\frac{F}{F_{\text{ref}}} \right)^{-\alpha}. \quad (3.6)$$

Henceforth the expected detection rate of bursts with fluence exceeding a given threshold F_l^x is:

$$R^x(F > F_l^x) = R^x = \frac{K}{\delta t_{\text{obs}}^x} \left(\frac{\nu_c^x}{\nu_{\text{ref}}} \right)^{-\beta} \int_{F_l^x}^{+\infty} \left(\frac{F}{F_{\text{ref}}} \right)^{-\alpha} dF. \quad (3.7)$$

Taking $\alpha > 1$, we can ensure the convergence of the integral in Eq. 4.1 and we obtain the following expression:

$$R^x = \frac{K}{\delta t_{\text{obs}}^x} \frac{1}{(\alpha - 1)} \left(\frac{\nu_c^x}{\nu_{\text{ref}}} \right)^{-\beta} \left(\frac{F_l^x}{F_{\text{ref}}} \right)^{-\alpha+1}. \quad (3.8)$$

Considering now Eq. 3.8 for both the NC and CHIME/FRB (CF) and calculating the ratios between the two equations, we can evaluate the rate of bursts expected at the NC with respect to the rate of bursts expected by CHIME/FRB as:

$$R^{\text{NC}} = R^{\text{CF}} \left(\frac{\delta t_{\text{obs}}^{\text{NC}}}{\delta t_{\text{obs}}^{\text{CF}}} \right)^{-1} \left(\frac{\nu_c^{\text{NC}}}{\nu_c^{\text{CF}}} \right)^{-\beta} \left(\frac{F_l^{\text{NC}}}{F_l^{\text{CF}}} \right)^{-\alpha+1}. \quad (3.9)$$

Lastly, the average number of bursts N^{NC} that we expect at the NC, with fluence greater than F_l^{NC} , throughout a campaign of total duration ΔT_c will be:

$$N^{\text{NC}} = R^{\text{NC}} \Delta T_c. \quad (3.10)$$

Instrument Fluence Detection Threshold

In order to evaluate the number of bursts throughout the campaign we need to estimate the minimum fluence detectable with the NC, given a certain S/N threshold. In general this fluence will depend on physical aspects of the incoming signal (e.g. the scattering) and also on the instrumental performances (e.g. the sampling time and frequency and hence the achievable resolutions). From the radiometer equation we can compute the minimum flux density S_l that we are able to detect with the NC, considering a minimum S/N of 10 (Burke-Spolaor et al., 2011):

$$S_l = S'_l \frac{\Delta t_m}{\Delta t}, \quad (3.11)$$

where

$$S'_l = 10 \times \frac{\text{SEFD}^*}{A \sqrt{N_p N_c d\nu \Delta t}} \zeta(\text{TOA}). \quad (3.12)$$

Δt_m consists in the measured width of the burst defined by Eq. 1.15. As we already mentioned, the signal will be generally broadened by the scattering time τ_s , the sampling time dt of the receiver and the intra-channel smearing, defined by Eq. 2.6. The quantity S'_l in Eq. 3.12 corresponds hence to the minimum flux density detectable in the case of negligible intra-channel smearing, scattering and sampling time.

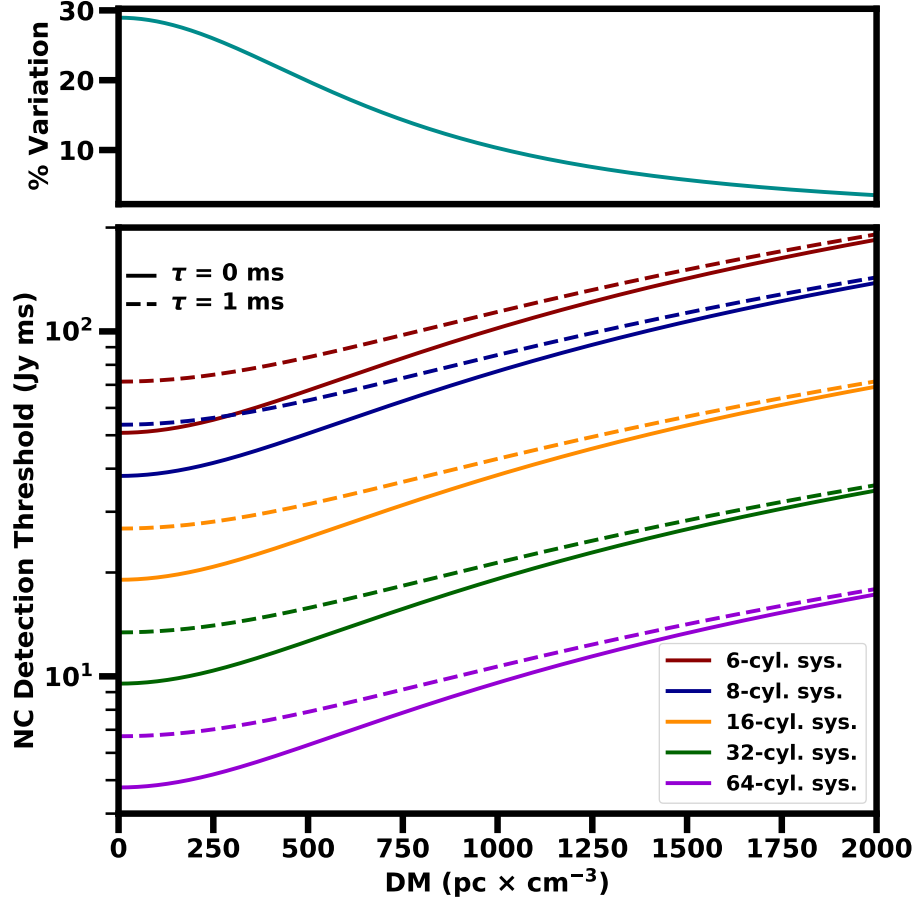


Figure 3.9: Northern Cross fluence detection threshold curves. The bottom panel shows the NC fluence detection threshold as a function of the DM computed via Eq. 3.13 considering a scattering time $\tau_s = 0$ (solid lines) and 1 ms (dashed lines), for the previous six-cylinders system (red), the current eight-cylinder system (blue) and the future sixteen, thirty two, sixty four-cylinder systems (orange, green, violet). The top panel represents the percentile variation between the threshold curve at $\tau_s = 1$ ms and the curve at $\tau_s = 0$.

Considering now a nominal width of a burst of $\Delta t = 1$ ms and assuming $\zeta = 1.5$ throughout the whole transit of the source³, substituting all the numbers in Eq. 3.11 we can express the minimum detectable fluence (at $S/N = 10$) F_l^{NC} of the instrument as:

$$F_l^{\text{NC}} = S_l(\Delta t = 1 \text{ ms}) \times 1 \text{ ms} \quad (3.13)$$

$$= \frac{690.12}{A} \frac{\sqrt{1.02 + \delta t_{\text{DM}}^2 + \tau_s^2} \text{ ms}}{1 \text{ ms}} \text{ Jy ms} . \quad (3.14)$$

Figure 3.9 displays the fluence detection threshold of the NC, computed via Eq. 3.13, as a function of DM. In addition to the previously considered values of 24 and 32 for the six and eight- cylinders systems, we consider $A = 64, 128, 256$ for the future sixteen, thirty-two and sixty-four cylinders systems, respectively.

The scattering time is more uncertain to estimate. We consider two cases: the case of zero scattering and the case of a scattering time of 1 ms. From Fig. 3.9 we see the detection threshold increase as the DM increases, consistently with the fact the DM smearing

³ ζ can actually vary between one and two throughout our observations, following the primary beam variations in a transit observation.

Table 3.3: Results for the NC observational campaign. For each source we report the observational system deployed (see Sec. 3.4) in the second column, the fluence detection threshold in the third column and the total observing time in the fourth column. For FRB 20180916B and FRB 20201124A we report in the fifth column the expected number of bursts N^{NC} , whereas for the other two sources we report the 95% confidence level lower limits of the slope of the differential fluence distribution α .

Source	System	F_t^{NC} (Jy ms)	ΔT_c (hours)	N^{NC}
FRB 20180916B	Six	51	112.7	1.4 ± 1.5
	Eight	38	70.4	1.3 ± 1.2
			183.1	2.7 ± 1.9
FRB 20201124A	Eight	44	68.14	1.0 ± 1.1

Source	System	F_t^{NC} (Jy ms)	ΔT_c (hours)	α
FRB 20181030A	Six	33	93.0	> 2.1
FRB 20200120E	Eight	42	109.2	> 2.2

dominates at higher DMs. As for the scattering time, from the top panel of Fig. 3.9 we see that it is quite relevant at low DM, whereas for DMs higher than 1000 pc cm^{-3} the relative variation between the two defined regimes is below 10%.

We estimate the minimum fluence that can be detected from the monitored sources using Eq. 3.13 and assuming $\tau_s = 0$.

In the case of FRB 20180916B, we can detect bursts with fluences greater than 51 and 38 Jy ms for the six and eight cylinders system respectively. FRB 20181030A has been monitored only when the six-cylinders system were in place and we estimate a fluence detection threshold of 44 Jy ms. FRB 20200120E and FRB 20201124A were both monitored with the eight-cylinders system and we place for them, respectively, a fluence detection threshold of 33 and 42 Jy ms.

With current upgrades in progress, when the full NS arm will be in use, we will lower our detection threshold to the order of some 5 Jy ms fluence at $S/N = 10$.

FRB 20180916B

Table 3.2 reports the flux densities and the fluences of the three bursts detected, computed from Eq. 3.4.

We compute the expected number of bursts from FRB 20180916B above our detection threshold by using Eqs. 3.10 and 3.9. In order to do so, we make the following assumptions. To calculate the average observing time of CHIME/FRB one needs to estimate the time when the source was within the FWHM of their beam at 600 MHz: we assume 70% of the computed transit time for the source⁴, yielding to 8.4 minutes per a single day.

With the NC we observed the source for approximately 66 minutes every day of the campaign. We take as CHIME/FRB pivotal value the burst rate to be $0.9 \pm 0.5 \text{ hours}^{-1}$ above a fluence limit of 5.2 Jy ms within its activity window of 5.2 days (Chime/FRB

⁴Source transit time can be computed thanks to the CHIME/FRB Online Calculator: <https://www.chime-frb.ca/astronomytools>

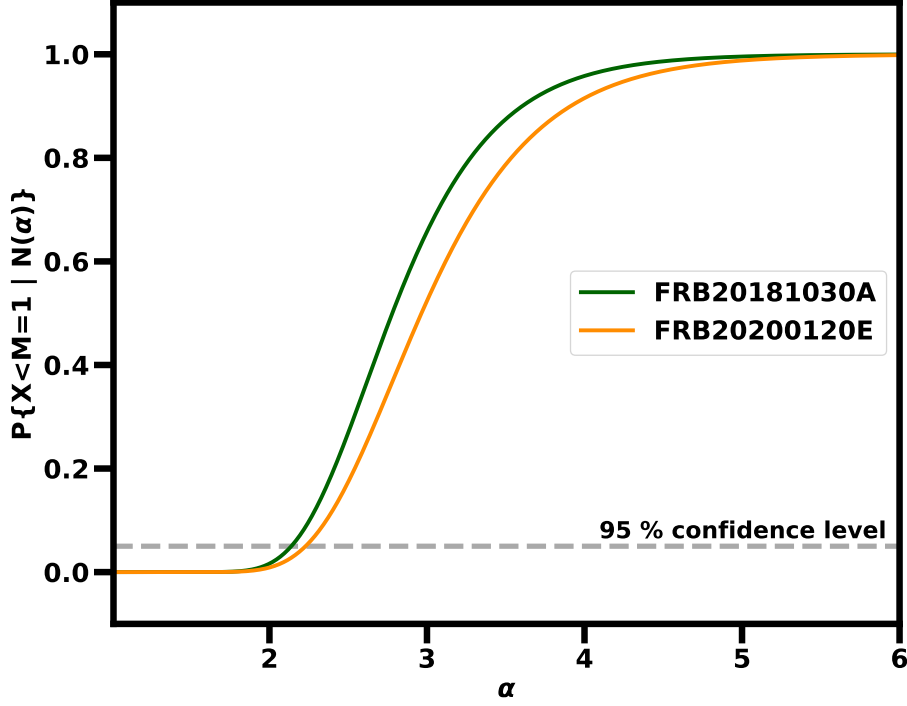


Figure 3.10: Cumulative Distribution Function of detecting zero events as a function of the slope of the differential fluence distribution α , for FRB20181030A (green line) and FRB20200120E (orange line). The horizontal dashed grey line demarcates the 5% probability of not finding bursts from FRB20181030A (FRB20200120E) with α less than 2.1 (2.2), implying that α has to be greater than 2.1 (2.2) with a 95% confidence level.

Collaboration et al., 2020). In Tab. 3.3 we report the expected number of bursts at the NC for ~ 102 hours (six-cylinders) and ~ 70 hours (eight-cylinders). We expect 1.4 ± 1.5 and 1.3 ± 1.2 bursts respectively, and a total of 2.7 ± 1.9 bursts for the total monitoring of ~ 180 hours. This result is consistent with our three detections. When the full NS arm will be operational, we can expect ~ 36 bursts from this source for a campaign of the same duration as the one performed.

FRB20181030A, FRB20200120E and FRB20201124A

No detections were obtained for FRB20181030A, FRB20200120E and FRB20201124A after an observing campaign of 93, 109 and 68 hours, respectively. We used our observations to constrain α , the slope of the fluence distribution for each source (see Eq. 3.5).

Following Amiri et al. (2017) and Paper I, if we assume that the occurrence of a burst is a Poissonian process, we can compute the likelihood of detecting M bursts with expectation number $N(\alpha)$ (computing this with Eq. 3.9 and Eq. 3.10) as:

$$p\{M; N(\alpha)\} = \frac{N(\alpha)^M e^{-N(\alpha)}}{M!} . \quad (3.15)$$

The cumulative distribution function (CDF) of seeing X events lower than M , with $N(\alpha)$ expected, can be expressed as:

$$P\{X < M | N(\alpha)\} = \sum_{k=0}^{M-1} p\{k; N(\alpha)\} . \quad (3.16)$$

Hence in the case of less than $M = 1$ events (non-detection case):

$$P\{X < M = 1 | N(\alpha)\} = e^{-N(\alpha)} . \quad (3.17)$$

In order to estimate $N(\alpha)$ we make some assumptions for the three sources. We separate the case of FRB 20181030A and FRB 20200120E from that of FRB 20201124A for reasons that we report below.

Figure 3.10 shows the CDF for the detection of zero events as a function of the slope α , for FRB 20181030A and FRB 20200120E, considering their respective total observing time (Tab. 3.3). In the cases of FRB 20181030A and FRB 20200120E, we assume a measured rate for CHIME/FRB equivalent to the predicted rate of the facility: $\sim 820 \text{ sky}^{-1} \text{ day}^{-1}$ above a threshold of 5 Jy ms at 600 MHz (The CHIME/FRB Collaboration et al., 2021). Under the same hypotheses as for FRB 20180916B, we set 13 min as the average observing time at CHIME/FRB for FRB 20181030A and 10 minutes for FRB 20200120E. The average observing times at the NC for the two sources were 90 and 72 minutes respectively.

Setting a confidence level of 95%, in Fig. 3.10 we can rule out the values of α for which the probability computed by Eq. 3.17 is less than 0.05. The lower limits obtained for the values of α for both sources are reported in Tab. 3.3. These limits are consistent with the estimated values of α for a low-DM population as showed by The CHIME/FRB Collaboration et al. (2021). In their work they searched for correlations between fluences and DMs among the current population of detected FRBs and found that the distributions of fluence versus α peak at two different values: $\alpha \sim 2$ for FRBs with DM between 100-500 pc cm^{-3} and $\alpha \sim 2.8$ for FRBs with DM $> 500 \text{ pc cm}^{-3}$. This is overall still compatible with the value of $\alpha = 2.5$ which is expected for an Euclidean Universe.

In the case of FRB 20201124A, Lanman et al. (2022) report a significant increase of the burst rate from the source in the period March-May 2021 with respect to the period between its discovery in November 2020 and March 2021, implying a non-Poissonian distribution of the events.

Due to this non-Poissonianity we only conservatively estimate the expected number of bursts above the estimated threshold for our facility for this source, in order to assess the compatibility with a non-detection. Following Lanman et al. (2022), we consider 4 minutes as the average observing time and a value of $\alpha = 4.5 \pm 2.2$ for CHIME/FRB. For CHIME/FRB we assume a rate of 5.4 hour^{-1} (see Fig. 3 of the aforementioned paper) above a fluence limit of 17 Jy ms. We observed this source with NC for 120 minutes on average. The expected number of bursts from FRB20201124A for the NC was calculated as 1.0 ± 1.1 , consistent with a non-detection.

3.7 Summary and Conclusions

This work presents the first FRB detections from the Medicina Northern Cross radio telescope, whose North-South arm is currently equipped to carry out FRB observations at 408 MHz with an observational bandwidth of 16 MHz. We performed a nineteen months observational campaign in which we targeted FRB 20180916B, FRB 20181030A, FRB 20200120E and FRB 20201124A.

We carried out tests and calibrations to upgrade the facility from six to eight cylinders. Before the upgrade we report the detection of a single burst from FRB 20180916B above a 10σ fluence threshold of 51 Jy ms (which also accounts for the intra-channel smearing for our current frequency resolution of 14.468 kHz). After the upgrade we report the detection of two bursts from the same source above a fluence threshold of 38 Jy ms. All bursts were

found within the 5.2 day activity window of the source, confirming the source periodicity. Assuming the CHIME/FRB source rate, we predicted the detection of 2.7 ± 1.9 bursts in our campaign, above the aforementioned fluence detection thresholds, consistent with our results.

We report no detections for the other three sources. In the cases of FRB 20181030A and FRB 20200120E, we constrain the slope of the differential fluence distribution α to be $\alpha > 2.1$ and $\alpha > 2.2$ at the 95% confidence level, respectively. In the case of FRB 20201124A we estimate 1.0 ± 1.1 bursts to be observed above a fluence detection threshold of 42 Jy ms, consistent with our non-detection.

The Search for a Multi-wavelength FRB

In this chapter we will focus our discussion on multi-wavelength observations of FRBs. The first section provides a review of the multi-wavelength campaigns performed on FRB sources. The second section will be completely dedicated to a particular source, the SGR J1935+2154, which became recently famous after its emission of an FRB-like signal prompt with a X-ray burst. The last part (from Sec. 4.3) will provide an original contribution: a year-long panchromatic campaign on FRB 20180916B which sets the most stringent upper limit to date to an optical counterpart simultaneous to a radio burst.

This chapter contains the results of the following work:

- **M. Trudu** et al., “*Simultaneous and panchromatic observations of the Fast Radio Burst FRB 20180916B*”, under review (A&A);

Contribution Statement: the results presented in this Thesis and reported in the aforementioned manuscript under review are part of a large collaboration. The multi-wavelength campaign involved several optical and high-energy telescopes. The observations and data reduction of these instruments, as well as the reported upper limits, are contributions provided by other coauthors of the manuscript. The detailed description of instruments outside the radio band is beyond the scope of this Thesis and we will leave the readers with several references, mentioned in each instrument paragraph, for more technical information. The manuscript first author contributions, which is part of the work done throughout his PhD, are: the concept and design of the manuscript, the manuscript draft, the data reduction of the radio instruments, the analysis and interpretation of the radio and multi-wavelength results and their discussion.

4.1 Multi-wavelength Observations of FRBs

The search for multi-wavelength (MWL) FRB counterparts is essential to unravel the nature of this yet enigmatic phenomenon. MWL observations are an asset in order to constrain the

FRB progenitors and the emission mechanism(s) behind them. MWL observations became particularly compelling after the simultaneous bi-chromatic detection (radio and X-ray) of a burst from the Galactic magnetar SGR J1935+2154, as we will discuss in greater detail in Sec. 4.2. Indeed, detecting a high-energy counterpart to an extragalactic FRB event, might lead either to further strengthening of the link between FRBs and magnetars (as many theoretical models suggest: see Sec. 1.3) or to the opening of new perspectives in the search for the FRBs’ progenitors.

Shortly after the detection of the first sample of FRBs by Thornton et al. (2013), the first extensive MWL campaign on an FRB source was set up, under the umbrella of a new survey devoted to search for FRBs at Parkes, dubbed SUPERB and running from 2014. First, a campaign was undertaken in order to look at the sky regions of the Thornton bursts, in order to find repeating bursts from these FRBs. No detection was reported, however a new FRB, FRB 20140514A (Petroff et al., 2015a), was discovered by the new SUPERB survey nearby the pointing of FRB 20110220A. Within few hours after the event, large MWL follow-up searches were performed in radio (Australian Telescope Compact Array, Effelsberg, GMRT and Parkes), in the optical band (GROND, Keck, Magellan, Nordic Optical, Palomar, SkyMapper, Swope telescopes) and with the high-energy satellite Neil Gehrels Swift Gamma-ray Burst Observatory (Swift). These follow-up observations did not identified a MWL counterpart, however Swift observations ruled out the presence of a possible GRB afterglow down to $8.2 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1}$ (0.3 – 10 keV band).

The discovery and precise localisation of the rFRBs, especially FRB 20121102A and 20180916B, later allowed for the first time to also conduct simultaneous MWL campaigns, rather than post-event searches. We will next focus on the MWL campaigns on these sources, and following Nicastro et al. (2021) we will divide the MWL observations performed as Radio+High-Energy and Radio+Optical/Near Infrared.

4.1.1 FRB 20121102A

Radio+High-Energy

Scholz et al. (2016) performed the first MWL campaign on FRB 20121102A. Throughout the campaign the source was observed in radio with Arecibo, Effelsberg, GBT, Lovell and VLA and in the X-rays with Swift (0.3 – 10 keV band) for about 10 ks and with Chandra (0.1 – 10 keV band) for about 40 ks. However, none of the 17 radio bursts detected were covered by neither Swift or Chandra. A second campaign (Scholz et al., 2017) with Chandra and XMM-Newton in tandem with Arecibo, Effelsberg and GBT was performed, this time with high-energy coverage simultaneous to radio detections. Again, no X-ray bursts were detected in 70 ks of high-energy observation. However this time it was possible to set 5σ confidence level upper limits (ULs) both for the persistent X-ray luminosity in the 0.5 – 10 keV, being $3 \times 10^{31} \text{ erg s}^{-1}$ and also for the energy of a prompt counterpart of $4 \times 10^{45} \text{ erg}$. Sun et al. (2021) performed an archival search (data from October 2016 to September 2017) for X-ray bursts in the 15 – 150 keV range of Swift, reporting no significant excesses and providing an energy UL of 10^{49} erg . NuSTAR and INTEGRAL were shadowing the MWL campaign led by Effelsberg (Cruces et al., 2021), with NuSTAR providing a 5σ energy UL in the 3 – 79 keV of $(0.6 - 5) \times 10^{47} \text{ erg}$. Eight year of Fermi/LAT archival data were searched for possible excesses by Zhang and Zhang (2017), providing a luminosity UL in the $10^{-1} - 10 \text{ GeV}$ range of $4 \times 10^{44} \text{ erg s}^{-1}$.

Radio+Optical/Near Infrared

Regarding the optical frequencies, Chatterjee et al. (2017) provides the first observations with the identification of a point-like source at the position of FRB 20121102A with the Keck and Gemini telescopes. A series of Sloan Digital Sky Survey data and Gemini Multi-Object Spectrograph observations (Tendulkar et al., 2017) showed that the host galaxy of FRB 20121102A is a low-metallicity, star-forming dwarf galaxy, with a stellar mass $4 - 7 \times 10^7 M_\odot$ and a diameter < 4 kpc, further constrained by Mannings et al. (2021) to be ~ 2 kpc via Hubble Space Telescope observations. Hardy et al., 2017 reports the first radio-optical observations with a monitoring of the source with Effelsberg in conjunction with the 2.4m Thai National Telescope. None of the 13 bursts reported have a plausible optical counterpart. In the previously mentioned work of Cruces et al., 2021 the Gran Telescope Canaria was observing, however the radio bursts were not covered by the optical observations.

4.1.2 FRB 20180916B

Radio+High-Energy

Scholz et al. (2020) reported observations of FRB 20180916B with CHIME, Effelsberg and Deep Space Network radio telescopes shadowed in X-ray by Chandra for 16 ks. Only one radio burst detected by CHIME was simultaneous with Chandra, providing a fluence UL of $5 \times 10^{-10} \text{ erg cm}^{-2}$ in the $0.5 - 10 \text{ keV}$ band.

Pilia et al. (2020) performed an ambitious campaign on FRB 20180916B not so long after the periodic activity assessment and precise localisation of the source. The campaign was led in radio by the SRT at P-band (328 MHz) and L-band (1547 MHz), supported by the NC telescope. The source was observed from 20–24 February 2020, for about 30 hours by SRT and about 7.5 hours with the NC, during one of the predicted activity windows of the source. Several high-energy satellites were on board: AGILE, INTEGRAL, NICER and XMM-Newton. The SRT detected three bursts, all of them happening within 20 minutes. Only AGILE and XMM-Newton were simultaneous to a radio burst detected and the other telescopes only provided non punctual ULs. AGILE energy UL was very interesting, being $E_{\gamma\text{-ray}} < 2.2 \times 10^{46} \text{ erg}$ (MeV range) punctual to the radio burst energy which was $E_{\text{radio}} \simeq 6.3 \times 10^{37} \text{ erg}$, implying an UL on the energy-ratio $E_{\gamma\text{-ray}}/E_{\text{radio}} < 5 \times 10^8$. This UL was compared with the 2004 giant outburst of the SGR 1806-20 (Palmer et al., 2005; Hurley et al., 2005), where the isotropic released energy was $E_{\gamma\text{-ray}} \simeq 2 \times 10^{46} \text{ erg}$, hence excluding giant bursts at least twice as bright as the SGR 1806-20 as a high-energy counterpart for an FRB. Searches in archival data of AGILE, made by Casentini et al. (2020), placed an UL on the persistent isotropic luminosity (energy range $> \text{MeV}$) of $< (5 - 10) \times 10^{43} \text{ erg s}^{-1}$. Tavani et al. (2020b) monitored the source with AGILE and Swift between February and March 2020, reporting a luminosity UL (0.3-10 keV range) of $1.5 \times 10^{41} \text{ erg s}^{-1}$. *Insight*-HXMT observed FRB 20180916B from 4–7 February 2020, and it placed a stringent UL on the released X-ray energy (1-100 keV range) for bursts lasting from 1 ms to 1 s being 10^{46} erg (Guidorzi et al., 2020).

Radio+Optical/Near Infrared

The first optical observation on FRB 20180916B were reported by Andreoni et al. (2020) with untargeted observations with the Zwicky Transient Facility. Pilia et al. (2020) and Zampieri et al. (2020) observed the source with the fast photometers IFI+Iqueye and Aqu-eye+, mounted at the Galileo and Copernicus telescopes (Asiago, Italy) respectively, and

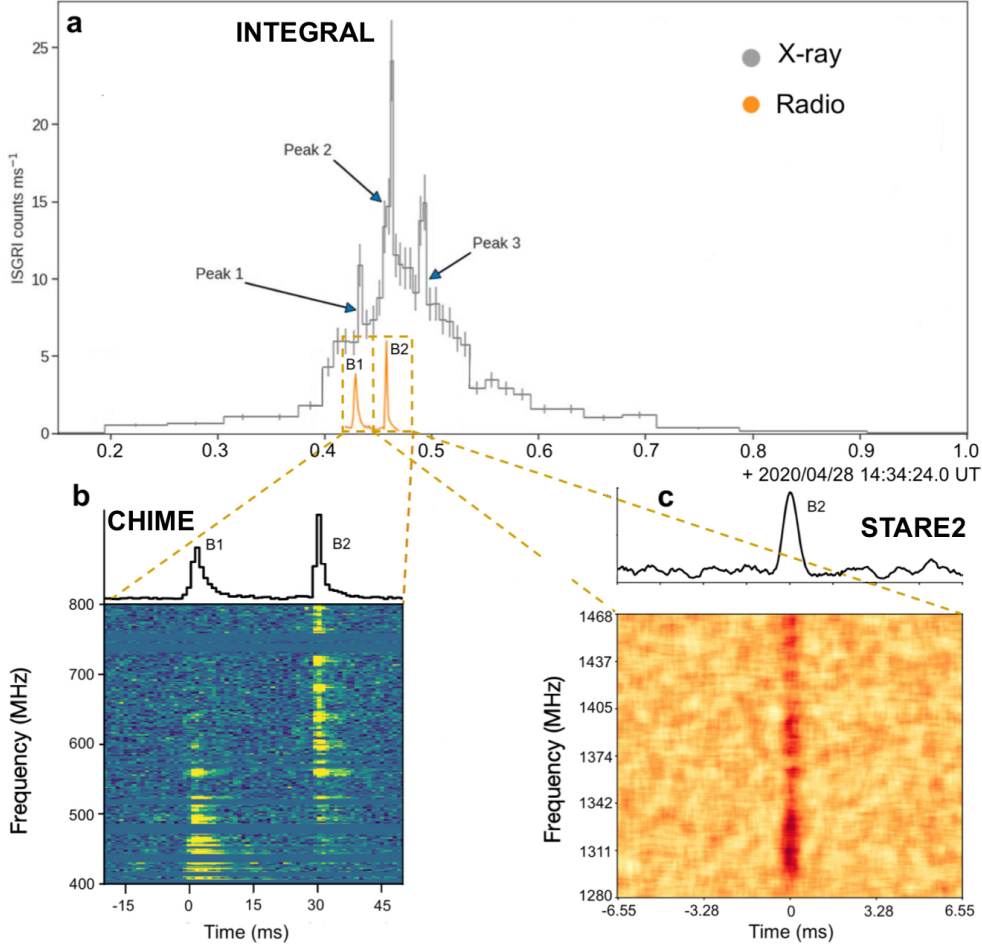


Figure 4.1: X-ray burst (a) from SGR J1935+2154 detected by the INTEGRAL IBIS/ISGRI instrument (20–200 keV) resulted to be simultaneous with two radio bursts (B1, B2) detected by CHIME at 600 MHz (b). B2 has been also detected by STARE2 at 1374 MHz (c). Image created by adapting figures from Bochenek et al. (2020b) (STARE2), The CHIME/FRB Collaboration et al. (2020) (CHIME), Mereghetti et al. (2020) (INTEGRAL).

the SiFAP2 photometer at the Telescopio Nazionale Galileo (TNG) in the same MWL campaign described in the previous paragraph. The SRT radio bursts however occurred during the daytime. Hubble Space Telescope observations performed by Tendulkar et al. (2021) showed that the location of the source is ~ 250 pc from the nearest active star forming knot of the host galaxy. Considering the typical velocities of pulsars, magnetars or NSs in binary systems, being in the range of $60 - 750 \text{ km s}^{-1}$, the authors state that FRB 20180916B would need $0.8 - 7 \text{ Myr}$ to travel from this putative birth site to its current location. This value appear to be in contrast with the typical active ages of magnetar, being of $\sim 10 \text{ kyr}$ and more compatible with the ages of high-mass X-ray binaries or γ -ray binaries.

4.2 The case of SGR J1935+2154

The Galactic SGR J1935+2154 has been discovered in 2014 by Swift. After a long monitoring with Chandra and XMM-Newton, Israel et al. (2016) showed that SGR J1935+2154 is a magnetar with period of 3.24 s with characteristic age of 3.6 kyr, surface magnetic field of $2.2 \times 10^{14} \text{ G}$ and spindown luminosity (in the X-ray) of $2 \times 10^{34} \text{ erg s}^{-1}$.

After its discovery, SGR J1935+2154 proved to be a quite active source, having bursting phases (outbursts) in 2015 and 2016 (Younes et al., 2017). On the 27th of April 2020 the source went in a new outburst phase (Borghese et al., 2020) emitting a storm of X-ray bursts (Fletcher and Fermi GBM Team, 2020; Palmer, 2020; Younes et al., 2020). The day after, CHIME detected two bright radio bursts from this source at 600 MHz (B1 and B2, see Fig. 4.1 b), about 30 ms apart (The CHIME/FRB Collaboration et al., 2020). Another radio burst was detected at 1374 MHz by the STARE2 array in the USA (see Fig. 4.1 c) and after considering the dispersive DM delay this burst has been shown to be consistent with B2 (Bochenek et al., 2020b). The detected bursts possess remarkably high fluences: being about 4.8×10^5 Jy ms for B1 and 2.2×10^5 Jy ms for B2 at the CHIME band, while the B2 fluence at STARE2 frequency is 1.5×10^6 Jy ms. The total delay due to dispersion gave an inferred DM of ~ 332 pc cm⁻³ in the observations from both instruments. NE2001 and YM16 Galactic DM predictions are in the range of 500 – 700 pc cm⁻³, confirming that the source is in the Galaxy as was already tentatively inferred (Zhou et al., 2020; Kothes et al., 2018), showing that the source is located within an uncertainty range of distance of 6.6 – 12.5 kpc from us. Assuming a fiducial distance of 10 kpc, CHIME reported a measured isotropic luminosity (considering B1 and B2 as a whole event) of $\sim 7 \times 10^{36}$ erg s⁻¹.

Simultaneously to these two bursts, the X-ray satellite *Insight*-HXMT detected a long (about a second) burst in the 1 – 250 keV band with two hard peaks separated by 34 ms, consistently with B1 and B2 (Zhang et al., 2020b). Mereghetti et al. (2020) reported nine X-ray bursts detected by INTEGRAL (20 – 200 keV band), with the seventh of them being temporally coincident with the radio bursts (see Fig. 4.1 a). The INTEGRAL burst lasted ~ 0.2 s and it shows three narrow peaks. In addition Konus/WIND (Ridnaia et al., 2020) and AGILE (Tavani et al., 2021b) detected an X-ray burst coincident with the radio bursts.

FAST started to monitor the source after the X-ray burst forest alert, covering 29 bursts from Fermi/GBM, and reporting no radio detections (Lin et al., 2020). However, two days after the CHIME/STARE2 discovery, the same authors reported the detection of a highly polarised radio burst with fluence of 6×10^{-2} Jy ms (Zhang et al., 2020a), way weaker than the two previously found. *Insight*-HXMT was in tandem with FAST and it did not detect any simultaneous burst in the 1-250 keV band (Li et al., 2020). About a month later two new radio bursts, with fluences 112 and 24 Jy ms were reported by Kirsten et al. (2021). In October 2020 CHIME reported the detection of three additional radio bursts (Pleunis and CHIME/FRB Collaboration, 2020). In October 2022 the source reactivated again with plethora of detections in the high-energies (see e.g. Roberts, Dalessi, and Malacaria, 2022; Palm, 2022; Younes et al., 2022; Li et al., 2022; Enoto et al., 2022; Wang et al., 2022; Frederiks et al., 2022, and cross references) and in radio (see e.g. Pearlman and Chime/Frb Collaboration, 2022a; Maan et al., 2022; Dong and Chime/Frb Collaboration, 2022; Pearlman and Chime/Frb Collaboration, 2022b, and cross references).

The various reported detections show that SGR J1935+2154 can either emit solely in X-ray or radio, with emission absent in the other respective wavelength, or in both EM bands, even though in this case the radio emission tends to be rarer. Moreover the radio bursts seem to not have a spin-phase dependence: the occurrence of the radio bursts compared with the folded X-ray light curve, appears to be stochastic, for instance with the radio bursts of CHIME/STARE2 of April 2020 being at the peak of the light curve and the radio bursts detected by Kirsten et al. (2021) happening not at the X-ray peak (see Fig. 5 from Younes et al., 2020). Furthermore there is a great variability in the radio bursts strength, spanning from few dozens of mJy ms to MJy ms. As yet, SGR J1935+2154, is the only Galactic source capable to fill the gap in luminosities and energetics among the known Galactic sources of strong radio pulses and the extra-galactic FRBs.

Table 4.1: Details of the radio instruments involved in the R3 MWL campaign. For each instrument we report the central frequency ν_c , observational bandwidth BW , sampling time dt and channel width $d\nu$.

Telescope	Receiver	ν_c (MHz)	BW (MHz)	dt (μs)	$d\nu$ (kHz)
SRT	L/P L-Band	1547	512	125	1000
	L/P P-Band	336	80	128	250
uGMRT	Band-3	400	200	81.92	97.65

In summary, SGR J1935+2154 paves the way for a link between magnetars and at least a subsample of the FRBs. In addition to the observational properties mentioned, Grossan (2021), by using the 161 X-ray bursts detected at the time, claimed that SGR J1935+2154 experiences a periodic phase of activity of ~ 251 days duration, with an activity window of ~ 140 days. If this finding will be confirmed/more accurately measured, it will further bolster the FRB/magnetar connection.

4.3 Simultaneous and Panchromatic Observations of FRB 20180916B (Original Contribution)

In the following sections, we report about the results of a MWL observational campaign which we carried out on FRB 20180916B between October 2020 and August 2021. The campaign was led in the radio band by the SRT at 336 MHz and the uGMRT at 400 MHz during eight activity cycles of the source. Simultaneous observations have been conducted by the optical telescopes Asiago (Galileo and Copernico), CMO SAI MSU, CAHA 2.2m, RTT-150 and TNG, and X/ γ -ray detectors on board the AGILE, *Insight*-HXMT, INTEGRAL and Swift satellites. We present the detection of 14 new radio bursts detected with the SRT and seven new bursts with the uGMRT from this source. We provide the deepest prompt upper limits in the optical band and in X-ray band for FRB 20180916B to date. In fact, the TNG/SiFAP2 observation simultaneous to a burst detection by uGMRT gives an upper limit $E_{\text{optical}}/E_{\text{radio}} < 1.3 \times 10^2$. A SRT P-band burst detected during an *Insight*-HXMT observation (1–30 keV) allowed to obtain an upper limit of $E_{\text{X-ray}}/E_{\text{radio}}$ in the range of $(0.9 - 1.3) \times 10^7$, according to which model is considered for the X-ray emission.

4.4 Observations and Data Reduction

We performed a MWL observing campaign on FRB 20180916B (R3 from now on), focusing on different activity cycles, from 2020/10/23 to 2021/08/30. In this section, for each wavelength, we report the specifications of the instruments used and how the data have been processed. The whole campaign, with all the telescopes involved and the observing times, is summarised in Fig. 4.2.

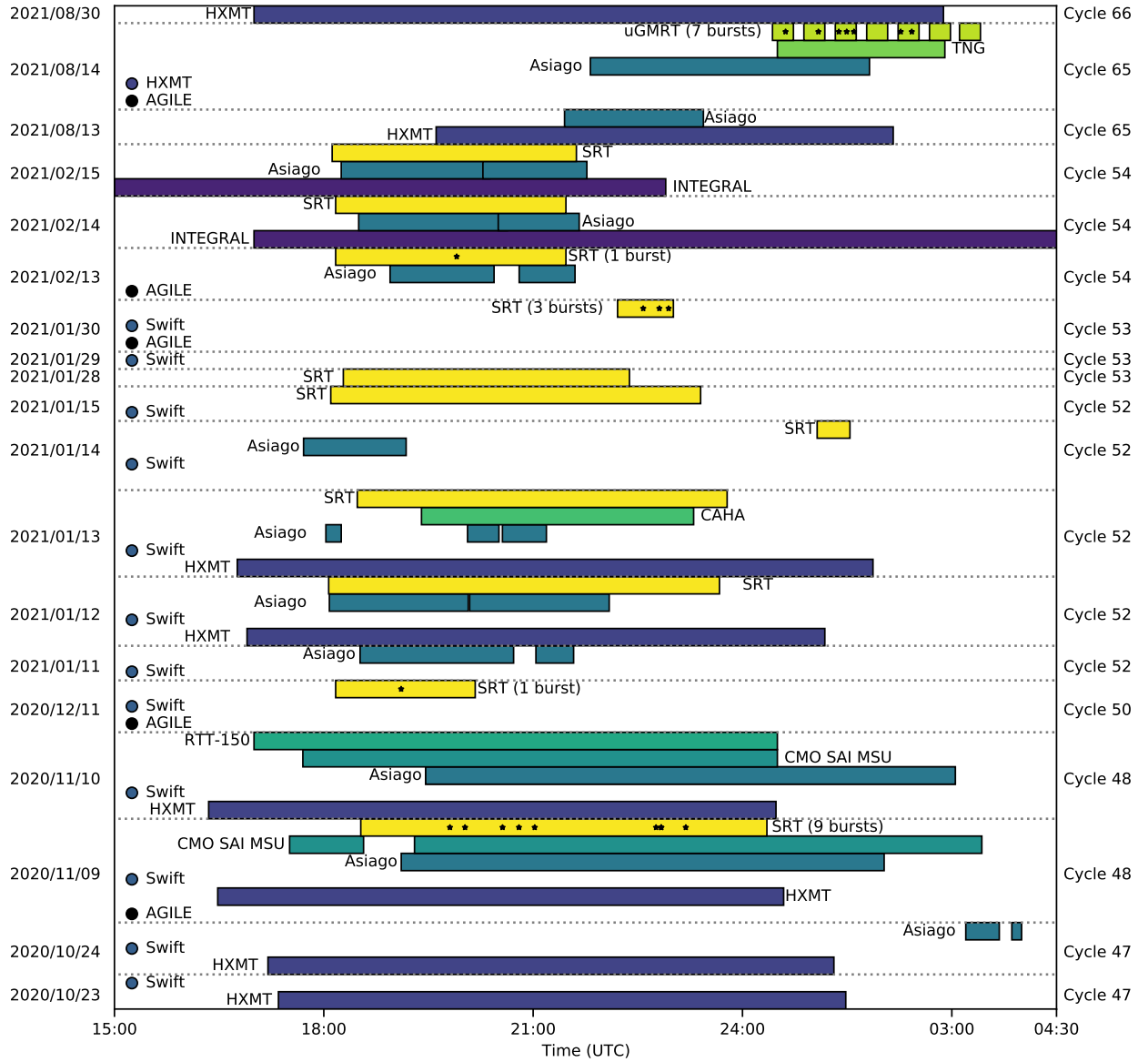


Figure 4.2: Observational R3 MWL campaign. Coloured bars represent observations performed for each facility as a function of time of the day (UTC). For each day (reported on the left) the corresponding activity cycle number of R3 is reported on the right. The time after 24:00 should be considered as part of the day after. Each detected radio burst is reported as a black star. AGILE and Swift (and *Insight*-HXMT on 2021/08/14) were observing throughout the whole day, except during epochs of visibility limitations (Earth occultations and South Atlantic Anomaly passages). The days in which a single instrument is present are scheduled days in which observations with other instruments have been cancelled.

4.4.1 Radio Instruments

SRT

The SRT monitored R3 from 2020/11/09 to 2021/02/15, for a total observing time of ~ 39 hours. The observations were made with the L/P dual band receiver (SRT-L and SRT-P, Valente et al., 2010), with observational central frequency of 1547 and 336 MHz respectively (see Tab. 4.1). The L-band data were recorded with the ATNF Digital Filterbank Mark III backend (DFB) whereas the P-band data were acquired via the ROACH1 backend (Bassa et al., 2016).

The L-band data were recorded as 2-bits per sample `psrfits` (Hotan, van Straten, and Manchester, 2004) search-mode files and subsequently converted into 8-bits `SIGPROC` (Lorimer, 2011) filterbank files; the P-band, after being recorded as `dada` baseband files, are coherently dedispersed at Dispersion Measure (DM) = $348.82 \text{ pc cm}^{-3}$ (CHIME/FRB Collaboration et al., 2019b), to remove the intra-channel smearing, and converted into 8-bits filterbank files using the `DSPSR` (van Straten and Bailes, 2011) routine `digifil`. The L-band receiver 512 MHz bandwidth is divided into frequency channels of 1 MHz each and time sampled at $125 \mu\text{s}$. The L-band data are originally recorded with a larger bandwidth of 1024 MHz to avoid aliasing effects. Radio Frequency Interference (RFI) typically affects less than 20 % of the nominal 512 MHz band. The 80 MHz bandwidth of the P-band is split into 320 channels of 0.25 MHz each and sampled at $128 \mu\text{s}$. The P-band bandwidth channels are generally corrupted by RFI for about a 30 %.

uGMRT

The uGMRT (Gupta et al., 2017) is an enhancement of the GMRT (Swarup et al., 1991) with improved receivers providing nearly seamless coverage from 50 to 1500 MHz and wide instantaneous bandwidths. The observations were carried out with the Band-3 receiver in the frequency range 300 – 500 MHz. The GMRT Wideband Backend (GWB, Reddy et al., 2017) was configured to split the 200 MHz bandwidth into 2048 spectral channels, giving a channel width of 97.65 kHz. At the time of the observation, the signals from 27 available antennas were combined in phase to give a phased array beam which was coherently dedispersed at $\text{DM} = 348.82 \text{ pc cm}^{-3}$. The real-time coherent dedispersion corrects only for the intra-channel dispersion, while the inter-channel dispersion is expected to be corrected offline. The array was rephased every 20 minutes to undo the phase drift due to ionospheric effects on the far away arm antennas. The calibrator 3C48 was observed for a few minutes initially to provide the flux scale for fluence calibration in case of bursts detection. Custom total intensity raw data produced by the backend are then converted into 16-bits `SIGPROC` filterbanks¹. The uGMRT observed R3 on 2021/08/15 for a total observing time of ~ 2.1 hours.

Single Pulse Search

The search for radio bursts from FRB 20180916B was performed using a search pipeline based on `Heimdall` (Barsdell et al., 2012), as similarly discussed in Sec. 2.4.3. As a first step, an RFI excision is made using the spectral kurtosis algorithm (Nita and Hellbourg, 2020) provided by the `YOUR` (Aggarwal et al., 2020) package. The flagged channels are then used by `Heimdall` via the option `-zap_chans` to ensure a deep RFI purging. The DM search was restricted to the range 300 – 400 pc cm^{-3} . For the SRT-P data we chose a S/N loss tolerance

¹<https://github.com/alex88ridolfi/ugmrt2fil>

in each DM trial of 1%. For the SRT-L and uGMRT data we performed a sub-banded search (as discussed in Sec. 2.4.1). In the case of SRT-L, the sub-banded search considered the full 1024 MHz dataset. In this way the search for bursts was performed within the nominal 1300 – 1800 MHz, but we also took advantage of the fact that the receiver passband filter does not have a sharp drop at its edges and a non-negligible fraction of the signal of a putative band-limited burst could appear outside the nominal borders of the band. We performed the sub-banded search by applying the following frequency windows: we took [1024, 512, 256] MHz windows (sub-banding level $Z = 2$) and we used a S/N tolerance of [1, 0.1] % with respect to the previously mentioned sub-band widths. For the uGMRT data we considered windows of [200, 100] MHz (sub-banding level $Z = 1$) and for each window a tolerance of [1, 0.5] %. In all the searches we used a maximum boxcar width of 500 ms.

In order to filter the high number of candidates found by `Heimdall` we considered some thresholds to sift them using the code `frb_detector.py`. We selected only candidates with $S/N \geq 6$, and minimum number of members (distinct boxcar/DM trial) clustered into a single candidate by `Heimdall` of 10. Lastly, all the candidates were visually inspected. Contrary to what was done in Sec. 2.4.3, we considered a lower S/N threshold as the source has a known DM and the number of observations allows a more feasible vetting for a single person, aimed by not missing weak events.

4.4.2 Optical Instruments

Asiago

Extensive optical coverage during periods of radio activity was attained with the fast photon counters Aqueye+ and IFI+Iqueye mounted at the Copernicus and Galileo telescopes, respectively, in Asiago (Zampieri et al., 2019; Zampieri et al., 2015; Naletto et al., 2009; Barbieri et al., 2009). The two instruments performed several observations of the area of the sky centered at the position of R3 (Marcote et al., 2020) at the dates reported in Tab. A.1 (some of them are simultaneous). Observations were performed in white light. At the beginning and at the end of each acquisition, a reference star close to the position of the target (2MASS 01580548+6542269, offset 44") was also observed to monitor the quality and transparency of the sky, i.e. to check that the count rate was constant and consistent with the expected value (according to the calibration relations in Zampieri et al. 2016). The same star (for Aqueye+) or another field star (2MASS 01580026+6541437, for IFI+Iqueye) was selected and carefully centred on the instrument camera for guiding purposes, in such a way that the FRB position matches the aperture of the on-source detectors or the fiber position. To this aim, an image of the field was previously acquired and astrometrically calibrated. The error of the target position registered on the image is $\sim 0.6''$, significantly smaller than the aperture/fiber diameter.

The photon event lists were reduced using a dedicated software (QUEST v. 1.1.5, Zampieri et al. 2015). Light curves with different bins were computed from the reduced event lists and searched for any significant rate increase. Periods of bad sky quality (count rate of the on-source detectors > 3700 counts/s for Aqueye+ and > 2600 counts/s for IFI+Iqueye) were discarded. The total useful on-source observing time was ~ 129.5 ks for Aqueye+ and ~ 62.1 ks for IFI+Iqueye (data discarded $\sim 10 - 20\%$). The count rate averaged over all acquisitions was 3038 counts/s for Aqueye+ and 1282 counts/s for IFI+Iqueye.

CAHA 2.2 m

The Calar Alto 2.2m telescope equipped with the AstraLux camera observed R3 for 3.3 hours starting on 2021/01/13 19:24:25 UT. A GG 385 longpass filter was used (White $\sim 667 \pm 237$ nm). AstraLux (Hormuth et al., 2008) uses an electron-multiplying, thinned, and back-illuminated 512×512 pixel CCD manufactured by Andor. It provides a field of view of $24'' \times 24''$ at a pixel scale of 47 mas/pixel. Using subarrays, binning, and short vertical shift times allows frame rates of more than 1 kHz. Operated as electron-multiplying CCD, as in the case of our observation, AstraLux can reach multiplication gains of up to 2500 with a linear response up to 70 photons per pixel.

Our observation was performed applying a 8×8 binning ($0.376''/\text{pixel}$) and acquisition rate of 200 Hz, which gives 64×64 bin frames, 5 ms integration time each. Split in 4 observing blocks due to the constraints of the acquisition software, we accumulated a total of 2,360,000 frames. In order to include in the field of view the G $\simeq 15.6$ reference star located North-West of the FRB position, an offset of $\delta\text{RA} \sim 8.8''$ and $\delta\text{Dec} \sim -7.3''$, with respect to the star, was applied to the pointing (see Fig. 4.3). The post-processing centre coordinates resulted to be R.A. = $01^{\text{h}}58^{\text{m}}00^{\text{s}}.60$, Dec. = $65^{\circ}43'01''.4$.

Custom software written in the IDL language was used to manage and analyse the custom AstraLux files. The procedure to identify a possible source onset consisted in aperture photometry at the FRB position, the mentioned reference field source and thirty additional “void” regions, as shown in Fig. 4.3. A three pixel extraction radius ($\sim 1.2''$) was adopted. Pointing drift was accounted for by monitoring the position of the reference source using 1-s accumulated images. The background was monitored in regions around the given positions (area of an external corona delimited by red circles in Fig. 4.3) whereas the bias level was computed from the average of the lower 12 rows of each frame to account for a variable, columns dependent variability. Frames time tagging precision is of the order of 0.1 s.

2.5 m CMO SAI MSU and 1.5 m RTT-150

We observed the position of R3 with the 2.5 m telescope of the Caucasian Mountain Observatory (CMO) of the Sternberg Astronomical Institute (SAI) Lomonosov Moscow State University (MSU). We used the Andor iXon 897 camera mounted on Cassegrain focus. This allowed us to obtain 4 ms frames (with 0.28 ms readout time). No optical filter was used in order to maximise the sensitivity. Due to software limitations, the time tag was rounded to 1 s, thus introducing a systematic error in the absolute timing. We selected a $80'' \times 20''$ field with two bright comparison stars with mean Gaia G magnitudes of 13.9 and 15.6: Gaia DR2 518385480138840704 and Gaia DR2 518386236053079936, respectively. The latter corresponds to the reference source observed by AstraLux. The angular scale after binning was $0.32''$.

We obtained about 14 hours of useful exposure over the nights of 2020/11/09 and 2020/11/10, with single series duration of 1200 s. For each individual series an averaged image was produced and astrometric corrections, with respect to known Gaia stars, were performed. Then for each single frame of the series we once again corrected the position with respect to the brightest star in the field (which produced about 750 electrons above the noise level per frame). This allowed us to obtain a typical accuracy of the astrometric solution of $0.2''$.

Over the second night of 2020/11/10 we also performed simultaneous observations with the Andor iXon 888 camera mounted on the 1.5 m Russian-Turkish Telescope (RTT-150), accumulating about 6 hours of data. No optical filter was used. We chose to select a single

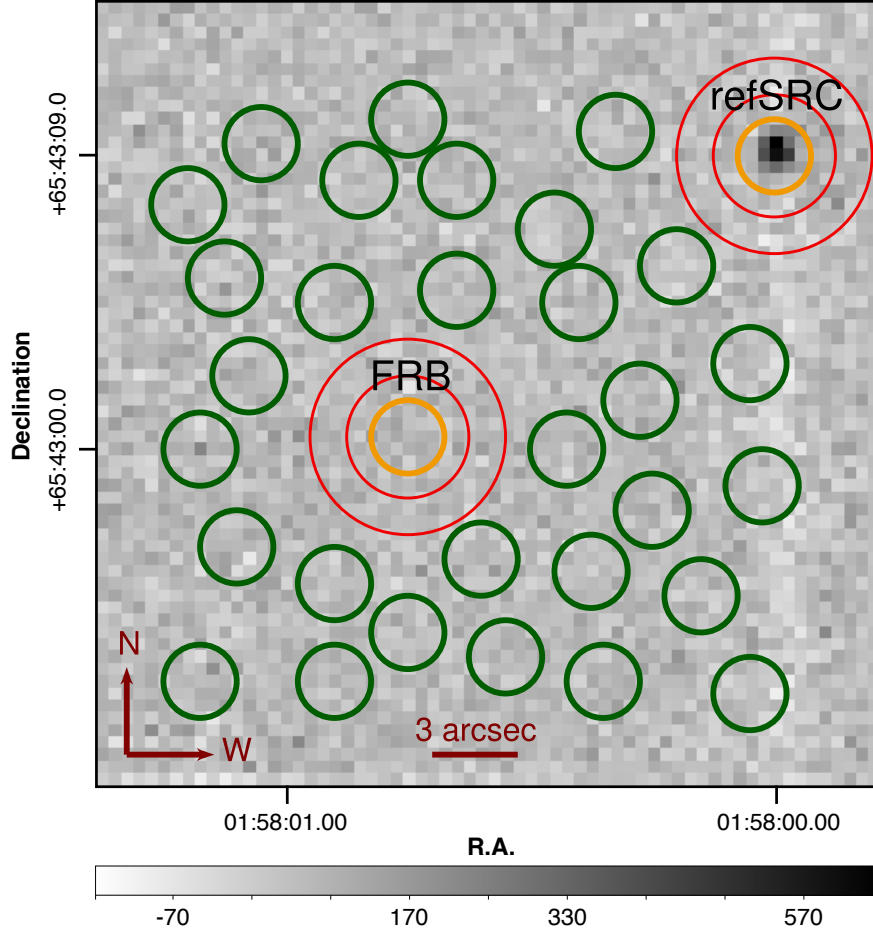


Figure 4.3: Sum of twenty 5-ms frames collected by AstraLux. The R3 position and the reference field source are marked by orange circles. The rings where the background was computed are marked in red. In green the thirty random regions whose aperture photometry and count statistics was investigated.

frame exposure of 8.24 ms with 0.1 ms readout time. The same two Gaia stars were used for astrometry. The expected noise signal distribution was acquired from the empty regions with no apparent stars in the field.

3.6 m TNG

We carried out a single observation of R3 with the fast optical photometer SiFAP2 (Ghedina et al., 2018; Ambrosino et al., 2016) mounted at 3.6 m INAF’s Telescopio Nazionale Galileo (TNG) located at Roque de Los Muchachos (La Palma, Canary Islands) on 2021/08/15. The observation was performed without any interruption starting at 00:35:00.000 UT and lasting 8.7 ks. No filter was used during the run to maximise the photon count rate. The final position of R3 was reached by offsetting the telescope from GSC2.2 N31321329057 star (R.A. = $01^{\text{h}}58^{\text{m}}05^{\text{s}}.50$, Dec. = $65^{\circ}42'26''.87$) with a pointing error $< 0''.5$, significantly better than the Field of View of SiFAP2 ($7'' \times 7''$). The sky background located $\sim 3.5'$ from the target was also monitored simultaneously with R3.

4.4.3 High-Energy Instruments

AGILE

The *AGILE* satellite observed the sky region in which R3 is located with its three detectors. The γ -ray imaging detector (GRID), sensitive in the range 30 MeV – 30 GeV with a 2.5 sr FoV, a coded mask X-ray imager, Super-AGILE (Super-A; operating in the energy range 18 – 60 keV; Feroci et al., 2007) with ~ 1 sr FoV, and the Mini-Calorimeter (MCAL), sensitive in the 0.4–100 MeV band with 4π non-imaging acceptance (Tavani et al., 2009; Tavani, 2019). *AGILE* is currently operating in spinning mode, with the instrument axis rotating every ~ 7 minutes around the satellite-Sun direction. For each satellite revolution, a large fraction of the sky ($\sim 40 - 60\%$) is exposed, depending on the Earth occultation pattern and trigger disabling over the South Atlantic anomaly (SAA, about 10% of the 95-min orbit). In particular, on timescales of hours $\sim 80\%$ of the entire sky can be exposed by the GRID γ -ray imager and by the MCAL.

AGILE has been involved in the MWL campaigns for FRBs since 2019, particularly for R3 (Tavani et al., 2020a; Casentini et al., 2020). The advantage to use an instrument like *AGILE* is closely related to its currently operating mode, the spinning. We are able to follow an FRB source minutes before and after each specific burst time with a small temporal gap. No evidence of γ -ray emission from these sources has been found so far (Verrecchia et al., 2021; Tavani et al., 2021a). *AGILE*-GRID exposure near burst times has been checked on short timescales (± 100 s around the bursts), and resulted in a partial coverage of the 21 bursts reported (only 12), due to SAA passages or Earth occultation. The long-timescale GRID analysis has been performed using the standard *AGILE* multi-source maximum likelihood (AML; Bulgarelli et al., 2012), usually applied to exposures longer than a few hours. We applied standard cuts to events, excluding SAA passages time intervals and events at off-axis angles greater than 60 deg or at angles from Earth direction smaller than 80 deg.

Insight–HXMT

Insight–HXMT is China’s first X-ray astronomy mission (Zhang et al., 2020c). It is equipped with three main X-ray instruments operating in the broad 1–250 keV band: the Low Energy (LE) X-ray telescope covers the 1–15 keV band (Chen et al., 2020); the Medium Energy

(ME) instrument covers the 5–30 keV band (Cao et al., 2020); and the 20–250 keV band is covered by the High Energy (HE) instrument (Liu et al., 2020). The time resolution of the LE, ME, and HE are 980 μ s, 255 μ s, and less than 10 μ s, respectively. The systematic errors of the timing system are 15.8, 8.6, and 12.1 μ s, for LE, ME, and HE, respectively (Tuo et al., 2022).

While the general procedure we followed to extract the light curves is the same as detailed in Guidorzi et al. (2020), in order to increase the exposure coverage of the observations we lifted some of the standard constraints employed to determine the good time intervals (Li C.-K. and Ji Long, personal communication). In particular, the *only* constraints passed to the `legtigen`, `megtigen` and `hegtigen` tasks were: Earth elevation angle $\text{ELV} > 1$ deg for LE and ME, $\text{ELV} > 0^\circ$ for HE; the pointing offset angle $\text{ANG_DIST} \leq 0.5^\circ$ for HE. For all the three instruments the `SAA_FLAG` (exclude the data in the South Atlantic Anomaly) was set to false.

The effect of this non-standard procedure is to not filter the data for high background regions. Because our pipeline estimates the background independently (Guidorzi et al., 2020), this does not affect our results. The advantage, on the other hand, is to cover a much larger time exposure, therefore increasing significantly the chance to find bursts.

The *Insight*–HXMT data analysis was performed with the software package HXMTDAS v2.04 and CALDB v2.05. We used the `hxbary` to apply the barycentric correction, thus converting the photons’ arrival terrestrial times (TTs) to the corresponding barycentric dynamic times (TDBs). LE, ME and HE instruments total on source exposure was of 127.7, 118.8 and 80.3 ks respectively. Table A.4 reports the observation log.

INTEGRAL

In total, between October 2020 and August 2021, INTEGRAL observed R3 for 658.0 ks (8.0 days) in 276 pointings. All of these data are currently public. INTEGRAL observations consist of approximately 1-hour-long pointings (binned at 1 s resolution), with a few hundred seconds slews in between. For the purposes of the observation log, we group them into longer observations, as long as the pointings are separated by no more than 300 seconds, as reported in Table A.5. The INTEGRAL data analysis has been conducted by using the standard INTEGRAL Offline Scientific Analysis software (version 11.0).

Swift

The Neil Gehrels Swift Gamma-ray Burst Observatory (Swift) observed R3 with the X-ray Telescope (XRT, Burrows et al., 2005), one of the three instruments equipped in the facility. The Swift/XRT data were obtained within the planned coordinate multi-instrument campaign started in 2020 whose first results have been partially reported in (Tavani et al., 2020a; Tavani et al., 2021a). We monitored R3 in the X-rays (0.3–10 keV) daily during 15 activity cycles (12 of them falling within the time intervals of this work). XRT observations were carried out in Windowed Timing (WT) readout mode, with 2–7 daily pointings. The time resolution of WT data is 1.8 ms and each pointing has a typical exposure of ~ 1.8 ks. We combined all the data within each proposal and processed them using the XRTDAS software package (v.3.7.0)² within the HEASoft package (v.6.30.1). The data were calibrated and cleaned with standard filtering criteria using the `xrtpipeline` task and the calibration files available from the Swift/XRT CALDB (version 20220803). The imaging analysis was executed selecting events in the energy channels between 0.3 and 10 keV and within a 20

²developed by the ASI Space Science Data Center (SSDC)

pixel ($\sim 47''$) radius, including the 90% of the point-spread function. The background was estimated from a nearby source-free circular region with the same radius value.

4.5 Results

4.5.1 Radio

Throughout the whole campaign the radio instruments, SRT and uGMRT, detected a total of 21 bursts (14 from the SRT at P-band and seven with the uGMRT). Figures 4.4 and 4.5 show the dedispersed (at $DM = 348.772 \text{ pc cm}^{-3}$, Nimmo et al., 2021b) waterfall plots of the bursts. Their properties are reported in Tab. 4.2.

The widths of the bursts were computed as the full width at half maximum of a Gaussian function. In the case of the SRT, the data have been converted into flux units applying the standard radiometer equation (Lorimer and Kramer, 2005), as discussed in Sec. 1.2.6. In the case of uGMRT, as we mentioned in Sec. 4.4.1, we calibrated the FRB data by multiplying it with a conversion factor counts-Jy estimated via on-source and off-source observations of 3C48 (Perley and Butler, 2017). The fluences F were computed by integrating the calibrated background subtracted light curves within their respective burst widths.

The P-band bursts detected by SRT do not possess complex structures, apart from the case of SRT-P-05 in which two sub-bursts of similar intensity are present. On the other hand uGMRT-03 shows the most complex morphology: the burst is composed by two sub-bursts, even though it is not possible to assess a clear separation between the two since the total intensity data cannot allow us to use a time resolution below the deployed $81.92 \mu\text{s}$. Six of the 21 bursts show a downward drifting toward lower frequencies (see Sec. 1.2.11), as already seen from this source (Chawla et al., 2020; Chamma et al., 2021). We evaluated the linear drift rate $\dot{\nu}$ by using a standard auto-correlation analysis (Hessels et al., 2019), obtaining values which scatter around an average value of $-10 \pm 1 \text{ MHz ms}^{-1}$ for the four bursts of SRT-P and $-8.2 \pm 0.8 \text{ MHz ms}^{-1}$ for the two bursts from uGMRT.

Regarding the SRT L-band, in addition to the standard single-pulse search, we carefully inspected the data for clustered bright pixels located $\sim 9.9 \text{ s}$ (the DM-delay between the top-frequencies of SRT-L and SRT-P) before the bursts at P-band. We do not report occurrence of a burst simultaneous at two different radio frequencies, as already noticed for R3 by Sand et al. (2022) and Pilia et al. (2020).

For the whole campaign, by exploiting the radiometer equation, we set a fluence UL (for a $S/N = 6$ 1 ms burst) of about 0.4 Jy ms at L-band. At P-band, for the dates in which we had no detection, we set a fluence UL of about 4.6 Jy ms .

Of the 14 SRT detections, nine happened on the same day. We observed R3 for 5.8 hours on 2020/11/09, implying an average burst rate of $\sim 1.55 \text{ hours}^{-1}$ at the SRT-P frequencies and above a fluence of 4.6 Jy ms . This value seems particularly high if compared, for instance, to the 2021/02/13 observation when we observed the source for 2 hours and detected only one event (corresponding to a burst rate of 0.5 hours^{-1}). In order to assess if the 2020/11/09 was a highly active day, as it frequently happens for FRB 2021102A (Zhang et al., 2018; Li et al., 2021; Hewitt et al., 2021; Jahns et al., 2022), we follow arguments similar to those discussed in Sec. 3.6.3 to obtain the rate of events expected by the SRT-P. We scale the rate reported for the source by CHIME/FRB of $R_0 = 0.9 \pm 0.5 \text{ hours}^{-1}$ at 600 MHz and above a fluence of 5.2 Jy ms (Chime/FRB Collaboration et al., 2020) to the SRT-P central frequency and fluence limit. We consider a value of $\beta = 1.5$ (Macquart et al., 2019) as the spectral index and a slope $\alpha = 2.3$ (Chime/FRB Collaboration et al., 2020) for the cumulative fluence

distribution $N(> F) \propto F^{\alpha+1}$ obtaining:

$$R(> F) = R_0 \times \zeta(\text{BW}, F_{\min}) \times \left(\frac{\nu_c}{600 \text{ MHz}} \right)^{-\beta} \times \left(\frac{F}{5.2 \text{ Jy ms}} \right)^{-\alpha+1}. \quad (4.1)$$

Here we additionally introduced a coefficient $\zeta(\text{BW}, F_{\min})$ to take into account the observational biases of the bandwidth BW of SRT-P to detect off-band events above its fluence sensitivity $F_{\min}$ as discussed by Aggarwal (2021). We estimated $\zeta(\text{BW}, F_{\min})$ via a Monte Carlo simulation. We model a burst from R3 as a Gaussian function in the frequency domain with the amplitude (energy), the frequency centroid and the FWHM width as free parameters. We assume the energy distributed in the range $(10^{36} - 10^{40})$ erg as a power-law with the same index α . The frequency centroids were drawn by a uniform distribution $\mathcal{U}(300, 1000)$ MHz excluding the LOFAR frequencies and frequencies $> \text{GHz}$ to avoid to add to the model the frequency-dependent activity of the source (see Secs. 1.2.13 and 1.4). Lastly the FWHM frequency widths were assumed Normal distributed $\mathcal{N}(\mu, \sigma^2)$, with mean value $\mu = 107 \text{ MHz}$ and standard deviation $\sigma = 59 \text{ MHz}$ obtained by considering the reported R3 frequency widths by CHIME/FRB (McKinven et al., 2022; Pleunis et al., 2021; Chime/FRB Collaboration et al., 2020; CHIME/FRB Collaboration et al., 2019b), since, with its 400 MHz observational bandwidth, it provides the least biased frequency width measurements. By simulating 1000 bursts for 1000 trials we obtain $\zeta(80 \text{ MHz}, 4.6 \text{ Jy ms}) = 0.33 \pm 0.04$ for the SRT-P.

Including all these parameters, Eq. 4.1 yields a burst rate $R(> 4.6 \text{ Jy ms}) = 0.7 \pm 0.4 \text{ hours}^{-1}$ for SRT-P, implying that the 2020/11/09 and 2021/02/13 rates were not outliers.

4.5.2 Optical

Asiago

We performed a search for any significant increase in the count rate on the 1 ms binned optical light curves of all acquisitions and, in particular, around the time of the detected radio bursts. All nine bursts detected with SRT in 2020/11/09, the single burst detected in 2021/02/13 and the seven bursts detected with uGMRT in 2021/08/14 fall inside Aqueye+ and/or IFI+Iqueye observing windows. The acquisitions of 2021/08/14 were contaminated by the activity of the Perseid meteor shower.

To assess the significance of a peak, we follow the procedure adopted by Zampieri et al. (2022) to search for optical bursts at the time of the occurrence of hard X-ray burst from the magnetar SGR J1935+2154. We assume a Poisson distribution with the average rate of the observation and fix a 3σ detection threshold $n_{t,\text{obs}}$ corresponding to a chance probability of $0.0027/N_{\text{trials}}$ in any of the bins of the observation. In case a radio burst is detected, we calculate also a detection threshold n_t corresponding to a chance probability of $0.0027/N_{\text{trials}}$ in any of the bins during an interval of $\pm 100 \text{ ms}$ and $\pm 15 \text{ s}$ around the time of arrival of the burst. These two values were chosen to estimate the significance in the two different scenarios of an optical burst almost coincident with the radio burst, and a delayed one. N_{trials} is the total number of bins in the interval. We obtain typical values of $n_{t,\text{obs}}$ in the range 18–20 counts bin^{-1} for Aqueye+ and 12–14 counts bin^{-1} for IFI+Iqueye. For the observations in which radio bursts were detected, we obtain $n_t(100\text{ms}) = 11\text{--}13$ counts bin^{-1} and $n_t(15\text{s}) = 15\text{--}16$ counts bin^{-1} for Aqueye+ (2020/11/09 and 2021/08/14; see Tab. A.1) and $n_t(100\text{ms}) = 6\text{--}8$ counts bin^{-1} and $n_t(15\text{s}) = 10\text{--}11$ counts bin^{-1} for IFI+Iqueye (2020/11/09 and 2021/02/13, see Tab. A.1).

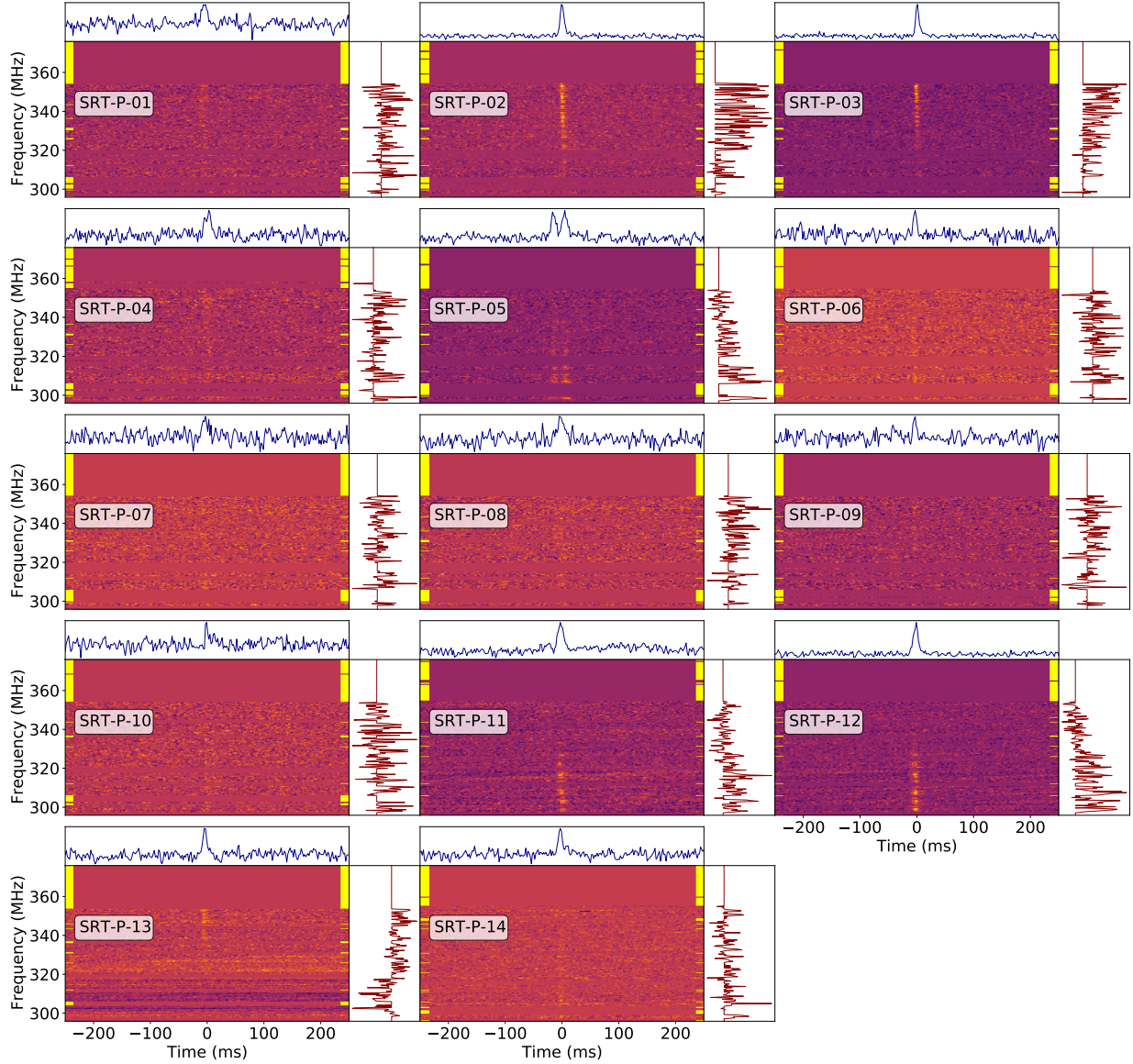


Figure 4.4: Bursts detected with the SRT. The data have a resolution of 0.5 MHz in frequency and 1.9 ms in time. For each burst, the top panel shows the frequency-averaged time series. The bottom left panel is the spectrogram of the signal and the bottom right panel is the time averaged (around the width of the burst) spectrum. The rows with the yellow ticks are masked channels due to RFI.

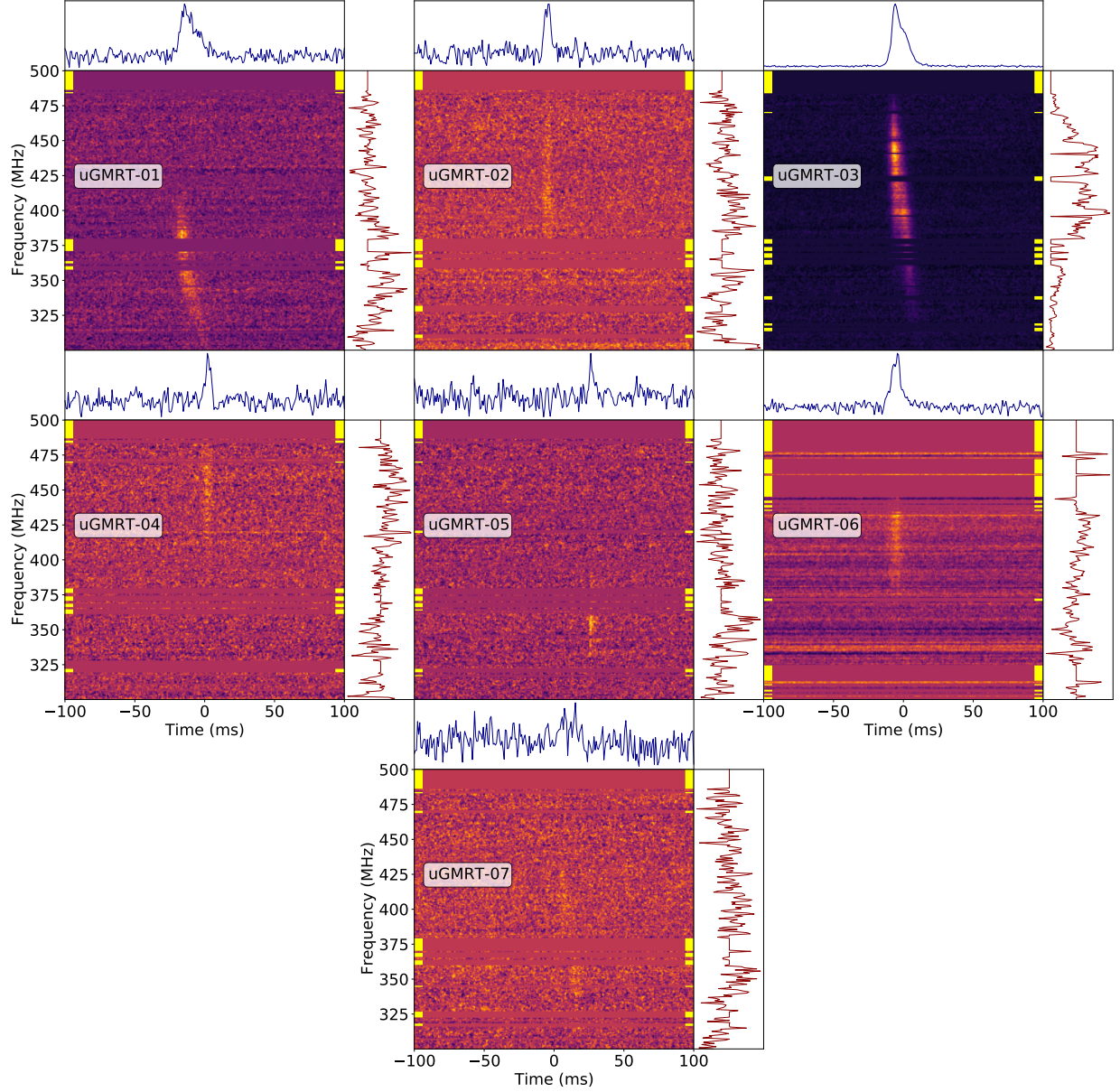


Figure 4.5: Bursts detected with the uGMRT. The data have a resolution of 0.8 MHz in frequency and 0.8 ms in time. For each burst, the top panel shows the frequency-averaged time series. The bottom left panel is the spectrogram of the signal and the bottom right panel is the time averaged (around the width of the burst) spectrum. The rows with the yellow ticks are masked channels due to RFI.

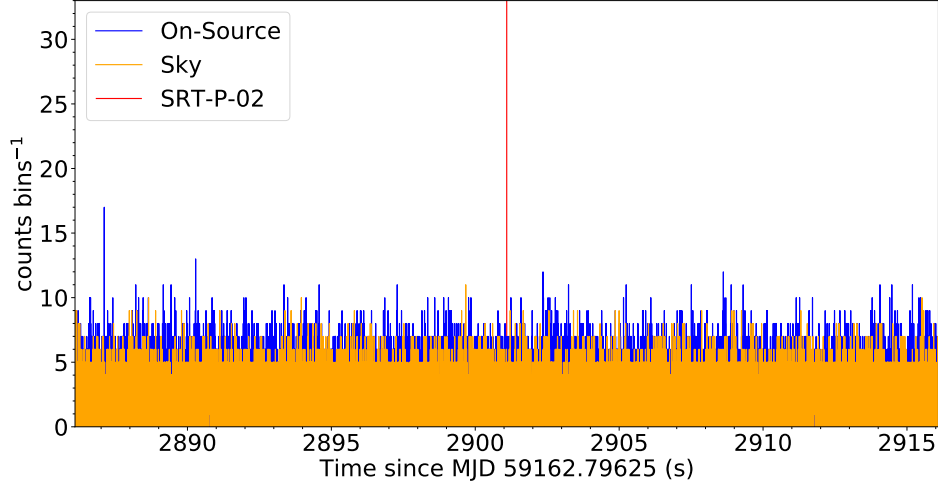


Figure 4.6: Light curves (binned at 1 ms) of the on-source (blue) and sky (orange) detectors of the Aqueye+ observation corresponding to R3, taken on 2020/11/09 (Obs ID 20201109-200635 in Tab. A.1). An interval of ± 15 s around the time of arrival of the burst SRT-P-02 (red vertical line) is shown.

Only one on-source optical peak with $n = 17$ counts bin^{-1} in an Aqueye+ observation falls inside an interval of ± 15 s around the time of arrival of SRT-P-02, with the optical leading the radio by 13.973 s (see Figure ??). This peak is slightly above threshold for the ± 15 s window ($n_t = 15$ counts bin^{-1}); corresponding to a potential detection at the 90% confidence level of an optical burst with 14.5 mag per ms, a specific fluence of 0.006 Jy ms, and a luminosity of 1.43×10^{43} erg s^{-1}), but slightly below threshold considering the entire observation ($n_{t,\text{obs}} = 18$ counts bin^{-1}). In fact, two other peaks are detected in the same observation, one with $n = 17$ counts bin^{-1} and the other with $n = 18$ counts bin^{-1} . We thus conclude that the optical peak is not significant enough to be considered a possible counterpart of the radio burst.

To estimate an UL to the optical brightness during a radio burst, we consider the highest on-source-only peak occurring in an interval of ± 100 ms and ± 15 s around the time at which a burst is detected, after subtracting a rate per bin that has a high Poissonian probability (99.73%) to be exceeded by chance in a single bin. This procedure returns an UL of 7–10 counts bin^{-1} (in ± 100 ms) and 12–16 counts bin^{-1} (in ± 15 s) for the two Aqueye+ observations of 2020/11/09 and 7–9 counts bin^{-1} (in ± 100 ms) and 11–14 (in ± 15 s) for the Aqueye+ observation of 2021/08/14. Using the V band calibration of Aqueye+ (Zampieri et al., 2016), these values correspond to an average (non extinction corrected) optical brightness of $V_{\pm 100\text{ms}} 14.25 - 14.64$ mag per ms and $V_{\pm 15\text{s}} = 13.74 - 14.05$ mag per ms for 2020/11/09 and $V_{\pm 100\text{ms}} = 14.49 - 14.64$ mag per ms and $V_{\pm 15\text{s}} = 13.88 - 14.15$ mag per ms for 2021/08/14. The corresponding deepest non extinction-corrected upper limits to the fluence are: 4.6×10^{-15} erg cm^{-2} (0.005 Jy ms) for an interval of ± 100 ms and 7.9×10^{-15} erg cm^{-2} (0.009 Jy ms) for an interval of ± 15 s in November 2020; 4.6×10^{-15} erg cm^{-2} (0.005 Jy ms) for an interval of ± 100 ms and 7.2×10^{-15} erg cm^{-2} (0.008 Jy ms) for an interval of ± 15 s in August 2021. Assuming a distance of 150 Mpc (Marcote et al., 2020), these values eventually imply the following limits to the luminosity: 1.2×10^{43} erg s^{-1} for an interval of ± 100 ms and 2.1×10^{43} erg s^{-1} for an interval of ± 15 s on 2020/11/09; 1.2×10^{43} erg s^{-1} for an interval of ± 100 ms and 1.9×10^{43} erg s^{-1} for an interval of ± 15 s on 2021/08/14.

The lack of detection of any optical peak during the partially simultaneous observations of 2020/11/09 with IFI+Iqueye confirms these results, although the inferred ULs are less

deep. IFI+Iqueye was the only active optical photometer in 2021/02/13, at the time of the SRT detection of SRT-P-14 (obs ID 20210213-195451; see Tab. A.1). The UL inferred for this observation are 7 counts bin^{-1} in ± 100 ms and 10 counts bin^{-1} in ± 15 s that, using the V band calibration of IFI+Iqueye (Zampieri et al., 2016) and the overall optical transmission efficiency at the time of the observation (32%), corresponds to an average (non extinction corrected) optical brightness of $V_{\pm 100\text{ms}} = 11.6$ mag $V_{\pm 15\text{s}} = 11.2$ mag. The corresponding ULs to the fluence (specific fluence) are 7.9×10^{-14} erg cm^{-2} (0.09 Jy ms) and 1.1×10^{-13} erg cm^{-2} (0.13 Jy ms), respectively.

On the other hand, significant optical peaks of duration between ~ 1 ms and ~ 10 ms are detected during some observations. While some are simultaneously observed with the on-source and sky detectors and are therefore diffuse foreground atmospheric events (most likely meteors), others are on-source-only or sky-only events the nature of which is still under investigation. Results of this analysis will be reported elsewhere.

CAHA

The $\simeq 2.4$ million 5-ms frames collected by CAHA 2.2m/AstraLux on 2021/01/13 were initially investigated for events deviating by more than 5σ from the background. We performed aperture photometry at the FRB position after removing frames affected by multi-pixels cosmic rays, which were not automatically filtered out by the analysis software. A conservative 6σ level cut allowed us to identify a total of 28 candidate events.

To quantify the statistical significance of this value, we performed the same analysis on the thirty void regions shown in Fig. 4.3. The resulting number of candidates was similar.

As a cross-check, the light curves obtained summing the counts collected on the FRB, void and reference source regions were statistically investigated. As expected, the distribution of net counts (centre $\simeq 4200$, $\sigma = 2130$) and the corresponding σ for the G $\simeq 15.6$ reference source clearly show its detection (see Fig. 4.7). In fact, the 1-s integrated light curve shows no sign of variability. On the other hand, for the FRB and void regions the bias subtracted count distributions are zero centred and narrower ($\sigma \sim 1400$). However, we note that only ~ 1 – 2 values exceed the 6σ level (~ 10 – 15 above 5σ). This is quite different from the figures obtained by the aperture photometry. Visual inspection of the frames with $\sigma > 6$ at the FRB location revealed two cases that we can consider of interest, occurring at 19:47:29.7 and 22:29:50.9 UTC. However, lacking a simultaneous monitoring with any other instrument, we cannot claim a burst detection. Based on the overall statistics of the reference source, we quote a limiting magnitude (White filter, not corrected for extinction) for the single 5 ms frame of 16.0 at 3σ and 15.5 at 5σ . The latter corresponds to an upper limit on the putative source luminosity of 5.3×10^{42} erg s^{-1} .

CMO SAI MSU and RTT-150

Over two nights we have accumulated about 12 million frames on the 2.5 m CMO telescope. For each frame we estimated the signal in a $2.5''$ (radius) aperture around the FRB position and also the background level in several selected regions. Mean signal in aperture was 20 electron. Assuming Poisson distribution of signal with this mean, probability to have more than one frame with signal larger than 48 electron from background in series of 1.2×10^7 frames is 0.37. A search for flux excursions with this threshold on individual frames was then performed. After manual screening of selected frames (which were caused by cosmic rays and detector anomalies) no viable candidate bursts was left. Assuming a linear response of the camera we could place a conservative UL on optical emission from the FRB position at a

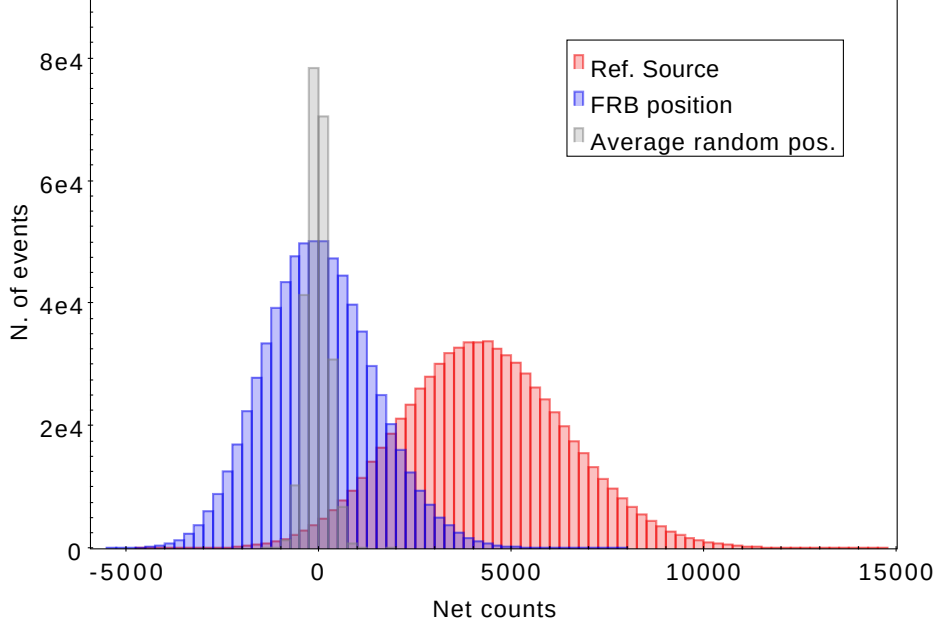


Figure 4.7: Count statistics comparison at the FRB (blue) and reference source (red) position. Here plotted 720 000 net counts from 5-ms frames collected by AstraLux in the first observing block. The statistics for the thirty random regions are comparable to that of the FRB region (grey).

level of 16.5 G magnitude per 4 ms frame. Taking into account the fact that the normalised response curve of our instrument deviates from the Gaia G band response curve by no more than 11%, we can put constraints on mean flux: $8.9 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$.

A similar analysis to the one described above was performed over the RTT-150 data. Apart from a few large amplitude outliers caused by the cosmic rays or CCD glitches no viable candidate events were found, providing an 5σ UL of about 15.5 G magnitude.

TNG

Seven bursts were detected by the uGMRT during the observation carried out on the night of 2021/08/14 (see Tab. 4.2) during which SiFAP2/TNG was observing for about 70 % of the total radio exposure time. As in the case of Asiago simultaneous observation (see Sec. 4.5.2 for more details), also our data were affected by the Perseid meteor shower, causing several high-significance spikes to be randomly distributed within the dataset of SiFAP2. We detected them on both detectors of SiFAP2 monitoring the target and nearby sky background, respectively (see Sec. 4.4.2). To search for possible optical counterparts of radio bursts, time of arrivals of single optical (320–900 nm) photons were rebinned at 1 ms resolution and computing our ULs with this resolution to be consistent with the results obtained by Asiago.

We searched for the optical counterpart in two different time intervals (± 15 s and ± 100 ms) around the epoch of the detection of all the seven bursts detected by uGMRT. Since no significant peaks were found at the time of bursts, we put only an upper limit on the magnitude. This value was computed for each burst by adopting the same procedure as that reported in Sec. 4.5.2. Following the SiFAP2 calibration curve³, we obtained a non dereddened UL magnitude of $V = 15.96(41)$, and $V = 16.42(44)$, for the ± 15 s and ± 100 ms time intervals, respectively. The corresponding fluences are 1.56 mJy ms and 1.02 mJy ms.

³<https://www.tng.iac.es/instruments/sifap2/>

4.5.3 High-Energy

AGILE

We searched in archival Super-A, MCAL and GRID data, at the times reported in Table 4.2, to look for coincident X-ray and γ -ray emission from the source. As we reported in Table A.3, *AGILE* has partial coverage of the 21 bursts reported. Of the 12 bursts in the MCAL FoV, we found no evidence of significant signals in the data. We could provide standard MCAL fluence ULs at 3σ when a data interval is present, and sub-ms fluence ULs when no data acquisition is available. Moreover, due to the *AGILE* spinning and to the reduced Super-A and GRID FoV with respect to the MCAL FoV, only 1 event falls inside the GRID exposed region and none in the Super-A one. However this burst falls within a data acquisition gap and hence we cannot provide a punctual UL. We could provide also GRID 3σ ULs in $E \geq 100$ MeV on two integrations: on 6 days, obtaining $UL_{6\text{days}} = 6.0 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$, and on about 17 months from 2020/04/01 to 2021/09/15, with $UL_{17\text{months}} = 7.7 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$.

Insight-HXMT

We carried out two kinds of search: (i) a blind one, regardless of the radio bursts, by applying the criteria that have already been tailored and applied to *Insight-HXMT* data in previous investigations (Guidorzi et al., 2020); (ii) a targeted search around the times of the FRBs that were covered with *Insight-HXMT* observations. The expected background counts were estimated following the prescriptions of Guidorzi et al. (2020). We did not find any statistically significant ($> 3\sigma$ confidence) candidate in either case. We hereafter focus on the results of (ii), whereas a more detailed report on the results of (i) will be reported elsewhere.

We observed simultaneously with *Insight-HXMT* 7 out of the 21 FRBs reported in this work (Table 4.2). In particular, we covered simultaneously with both LE and ME 5 FRBs detected with the SRT (SRT-P-01, SRT-P-02, SRT-P-07, SRT-P-08, and SRT-P-09), whereas uGMRT-01 was covered with all of the three *Insight-HXMT* instruments and uGMRT-02 with the ME only. For each of these 7 FRBs we carried out a search for statistically significant excesses within a time window centred on the FRB time with a duration of 200 s or shorter, depending on the availability of data. To account for the unknown duration of any possible high-energy counterpart, we spanned a logarithmically-spaced range of bin times, from 1, 2, 4, ... to 128 ms. In each case we applied a threshold on the counts of each individual detector as well as to the summed counts, by imposing a detection significance of $p_{\text{sing}}/N_{\text{bins}}$, with p_{sing} as close as possible to 2.7×10^{-3} (i.e., 3σ confidence), taking into account the multitrial due to the number of bins N_{bins} to be screened. Since the expected background counts in each instrument are $\ll 1$ over a few ms and because of the discreteness of Poisson distribution, the probability associated with a given threshold on the number of counts varies enormously even by changing the threshold by one: this is why the corresponding significance can only approximately be 3σ for most cases.

In no case we found counts in excess of the thresholds. We therefore calculated the threshold counts on the summed light curves (LE+ME for the 5 SRT FRBs, LE+ME+HE for uGMRT-01, and ME only for uGMRT-02) for three representative bin times (1, 16, and 128 ms). We then converted these ULs on counts to corresponding fluence values by considering three different spectral models that were discussed by Guidorzi et al. (2020) and that can be plausibly expected for sources like magnetars: a power-law (PL) with photon index $\Gamma = 2$, an optically thin thermal bremsstrahlung (OTTB) with either $kT = 50$ keV or $kT = 200$ keV.

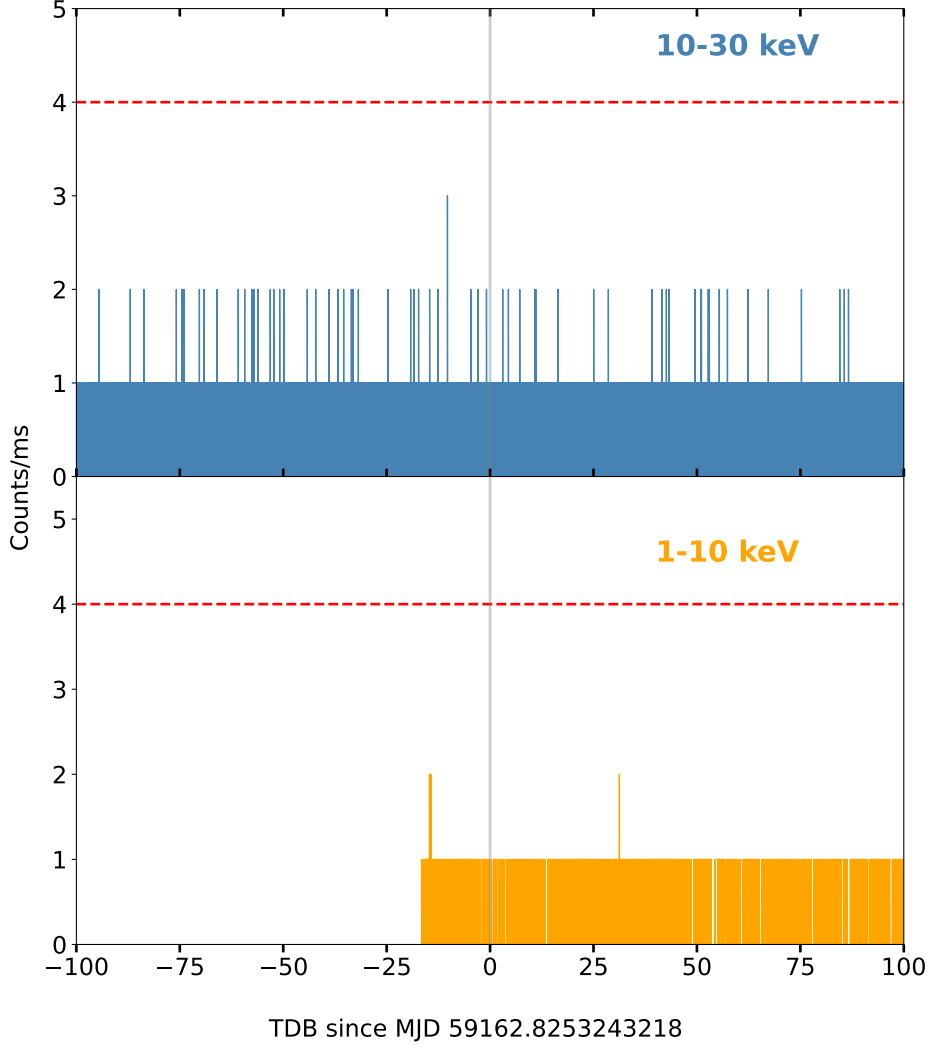


Figure 4.8: *Insight*-HXMT 1-ms light curves of LE and ME obtained around SRT-P-01. Dashed lines show the $\sim 3\sigma$ upper limits that account for the multi-trial search.

Table A.8 reports the corresponding fluence limits in either 1 – 30, or 1 – 100, or 10 – 30 keV energy passbands, depending on whether data from LE and ME only were available, or from all of the three instruments, or from the ME only, respectively. Overall, for each of the three integration times mentioned above, the corresponding $\approx 3\sigma$ ULs on the 1 – 30 keV fluence are in the range $(1.6 - 2.9) \times 10^{-10} \text{ erg cm}^{-2}$ (1 ms), $(2.7 - 5.5) \times 10^{-10} \text{ erg cm}^{-2}$ (16 ms), and $(5.5 - 12) \times 10^{-10} \text{ erg cm}^{-2}$ (128 ms).

Figure 4.8 shows the *Insight*-HXMT coverage with 1 ms resolution of SRT-P-01 with LE and ME, along with the corresponding $\approx 3\sigma$ detection threshold.

INTEGRAL

In the complete integrated mosaics of ISGRI and JEM-X we do not detect bursts from R3 and we use ISGRI observations to set an UL of $1.1 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ on average source flux in 28 – 80 keV band assuming a power-law spectrum with a slope of 2. The limit on average source flux with JEM-X can be set in 3 – 30 keV band at the level $3.6 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$.

In order to search for possible variable emission, we built ISGRI light curves on timescales of 1000 seconds and 1 second, in 28-80 keV energy range. We do not detect any variable emis-

sion on these timescales and put ULs of $2.7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $1.1 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ on 1000 seconds and 1 second long impulsive emission.

Unfortunately, none of the bursts occurred when R3 was in the FoV of INTEGRAL pointing instruments. However, INTEGRAL all-sky instruments were taking data during all of the radio events, and we derive an UL on 1-second long hard X-ray burst within 10 seconds from each radio burst, as shown in Tab. A.6.

Swift

We carried out a search for the presence of an X-ray source candidate at the R3 position in the whole Swift/XRT WT mode dataset. No X-ray source was detected (a $> 3\sigma$ confidence was required). We therefore extracted the 3σ countrate ULs using the XIMAGE package (sosta command) and converted to fluxes using a standard single power-law spectral model with photon index 2.0, and correcting for absorption for a column density N_H fixed to the Galactic value of $7.1 \times 10^{21} \text{ cm}^{-2}$ (HI4PI Collaboration et al., 2016) redshifted for the known $z = 0.0337$ (Marcote et al., 2020). The X-ray observations exposure and the corresponding ULs are reported in Tab. A.7.

4.6 Discussion

Figure 4.9 shows an overview of the isotropic luminosity ULs by all the instruments involved in this MWL campaign. We can use these punctual ULs to constrain the optical/radio and high-energy/radio energy ratios. During the night of 2020/11/09, SRT-P-02 was observed simultaneously with Aqueye+ and CMO SAI MSU. Assuming that the burst width is of the same order of tens of ms in both bands, this implies a ratio $\xi = E_{\text{optical}}/E_{\text{radio}} < 7.8 \times 10^2$ and $\xi < 5.6 \times 10^2$, respectively. CMO SAI MSU UL however, is obtained from a camera (iXon 897) while Asiago uses a fast photometer (Aqueye+) and the observations are performed and reduced via different techniques. In the case of the search for an optical counterpart of a signal like an FRB, due to its short duration, a fast photometer is more capable to explore such low duration ranges. The radio burst uGMRT-03 was simultaneous with Aqueye+ and SiFAP2 observations and, with their punctual UL, we can constrain the ratio $\xi < 6.9 \times 10^2$ for Aqueye+ and $\xi < 1.3 \times 10^2$ for SiFAP2. SiFAP2 UL on R3 is the most stringent UL on the optical emission for this source to date. The previous most stringent UL in the optical band for R3 was from Andreoni et al. (2020). They performed untargated observations of R3, not simultaneous with a radio instrument, with the Zwicky Transient Facility, monitoring the source in active windows and providing an UL of $\xi < 10^8$.

Beloborodov (2020) describes a scenario where young, hyperactive magnetars are the progenitors of FRBs. Their magnetic flares are able to generate blast waves in the surrounding wind medium and this could result into optical flashes, of the duration of up to $\sim 1 \text{ s}$, simultaneous to the radio bursts. Given their formation, in the tail of a preceding flare, they are expected during recurrent flaring episodes, and they are expected to be weak unless they are formed after a strong explosion, when they could reach $E_{\text{optical}} \sim 10^{44} \text{ erg}$. Our current UL, for both dates when more bursts were observed, at the moment can only exclude such strong flares.

SRT-P-02 was also simultaneous with *Insight*-HXMT observations, which provided a punctual UL (1–30 keV band) on the released isotropic energy $E_{\text{X-ray}}$, in the range of $(2-3) \times 10^{45} \text{ erg}$ for a time bin of 128 ms, according to which emission model is considered (see Sec. 4.5.3). This UL is of the same order of magnitude of the ones placed by Chandra (Scholz

et al., 2020) and XMM-Newton (Pilia et al., 2020) for the same source also simultaneously with a radio burst. In the case of the SRT-P-02 burst, this UL implies an UL in the X-ray/radio efficiency $\eta = E_X/E_{\text{radio}} < (0.9 - 1.3) \times 10^7$.

It is worth to make a comparison with the case of the SGR J1935+2154 event. With its bi-chromatic simultaneous detection in radio (The CHIME/FRB Collaboration et al., 2020; Bochenek et al., 2020b) and at high-energies (Mereghetti et al., 2020; Tavani et al., 2021a; Zhang et al., 2020b; Ridnaia et al., 2020), it provided evidence that magnetars can be FRB emitters and hence be the sources behind at least some of the FRBs observed. In that case, the energy released for the burst detected by CHIME was $\sim 3 \times 10^{34}$ erg and it corresponded, in the 1–250 keV band of *Insight*-HXMT, to $\sim 1 \times 10^{39}$ erg (Zhang et al., 2020b), implying $\eta \sim 10^5$. This value is two orders of magnitude smaller than the η UL that we reached with our MWL observations for R3. Our current UL means that if an X-ray burst similar to the one from the SGR J1935+2154 happened simultaneously with SRT-P-02, this putative burst cannot be more than 10^7 times more energetic than the radio one. However with this current UL we cannot exclude X-ray/radio efficiencies η ten times greater or of the same order of magnitude of the efficiency of the SGR J1935+2154 event.

If we compare the results of our multi-cycle MWL campaign on R3 to the evidence based on the single event associated to the SGR J1935+2154 burst, we conclude that the detection of a R3 radio burst with fluence 10^3 Jy ms would allow us to set constraints on η matching those of the Galactic event, in light of the sensitivity thresholds of current X-ray telescopes.

If we determine the sensitivity of a given X-ray instrument as $F_{\text{X-ray}}^*$, we can express the corresponding radio fluence F , with the assumption of an efficiency η as:

$$F = \frac{F_{\text{X-ray}}^*}{\eta \Delta\nu} , \quad (4.2)$$

where $\Delta\nu$ is the frequency width of the radio burst. We assume the average value of $\Delta\nu = 107 \pm 59$ MHz as discussed in Sec. 4.5.1. We can now compute via Eq. 4.1 the rate of events $R(> F)$ with radio fluence greater than F for the SRT-P and uGMRT Band 3. By performing the same Monte Carlo simulation for uGMRT Band 3, we obtain a value of $\zeta(200 \text{ MHz}, 0.6 \text{ Jy ms}) = 0.43 \pm 0.04$.

Adopting the assumption that the R3 bursting activity is Poissonian, using the expected rate $R(> F)$, we can roughly estimate the detection probability $p(> F)$ of detecting one or more bursts with fluence $> F$ in a campaign of duration ΔT :

$$p(> F) = 1 - e^{-R(> F)\Delta T} . \quad (4.3)$$

Figure 4.10 shows the probability computed via Eq. 4.3 for an X-ray detection simultaneous with the SRT-P or the uGMRT Band 3 as a function of the time of simultaneous exposure. Evaluating how much a certain X-ray satellite is sensitive to a putative X-ray burst requires several assumptions on the emission mechanism of the source in order to get a punctual value for $F_{\text{X-ray}}^*$. Keeping the discussion to the level of orders of magnitude, the X-ray telescopes involved in the campaign were capable to detect bursts with a fluence sensitivity in the range of $10^{-10} - 10^{-7} \text{ erg cm}^{-2}$. Considering a 99.9 % detection probability, this would require X-ray/radio campaigns $3 \times 10^2 - 3 \times 10^6$ hours long for $\eta = 10^6$, or $6 \times 10^3 - 5 \times 10^7$ hours for $\eta = 10^5$, with respect to the X-ray sensitivities considered.

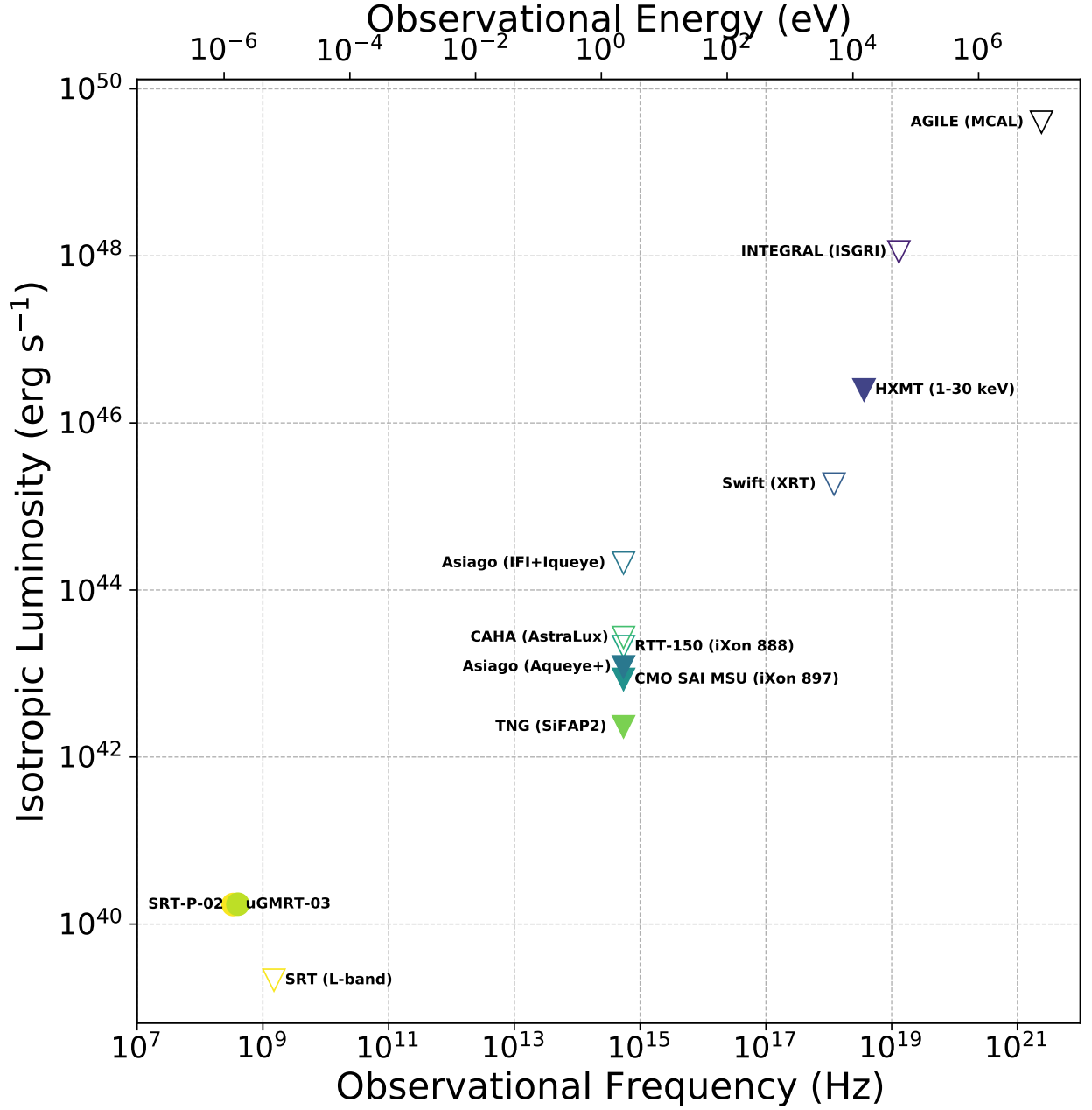


Figure 4.9: Burst isotropic luminosity as function of the observational frequency for all the instruments involved in the MWL campaign. The dots are the luminosities of the bursts SRT-P-02 and uGMRT-03. The empty triangle markers represent the non punctual upper limits (ULs), that is coincident with no radio burts. The filled triangles are punctual ULs, coincident with a radio burst detection (see Sec. 4.6). All optical ULs are converted in the V band and for a 1 ms burst.

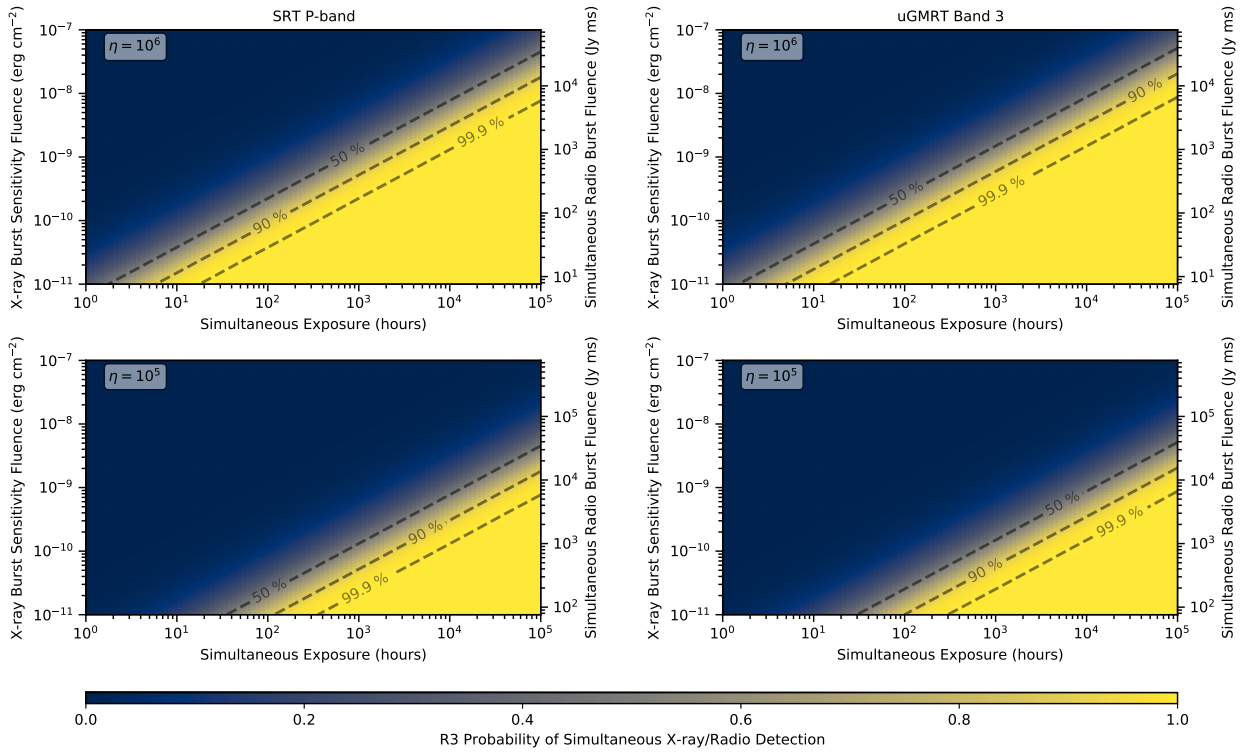


Figure 4.10: Probability of detecting a X-ray/radio event given a certain X-ray/radio efficiency η observing in the radio band with the SRT-P (left) or the uGMRT Band 3 (right). Supposing that the event is above the fluence X-ray sensitivity (left y-axis) the colormap shows the probability of detecting a radio burst with radio fluence (right y-axis), constrained by the efficiency η , as a function of the simultaneous exposure (x-axis). The dashed lines represent the iso-probability contour plots for a probability of 50, 90 and 99.9 %.

4.7 Summary and Conclusions

This work presents the results of a multi-wavelength observational campaign on FRB 20180916B (R3) performed between October 2020 and August 2021. The campaign involved the SRT and the uGMRT radio telescopes, the Galileo and Copernico (Asiago), CMO SAI MSU, CAHA 2.2m and RTT-150 optical telescopes, and lastly the high-energy satellites AGILE, *Insight*-HXMT, INTEGRAL and Swift.

We detected 14 new bursts with the SRT at 336 MHz and seven new bursts with the uGMRT at 400 MHz. Neither the optical instruments nor the high-energy ones detected statistically significant bursts at their frequencies. Asiago reports an optical peak within a window of ± 15 s around the second radio burst detected by the SRT on the night of 2020/11/09. The peak is slightly above the threshold of the aforementioned window of 30 s of 15 counts bin^{-1} . However, it is below the 18 counts bin^{-1} threshold obtained considering the statistics of the entire observation, thus not making it possible to robustly tag it as the optical counterpart of the radio burst.

We constrained the optical/radio efficiency ξ setting a punctual upper limit (UL) thanks to a radio detection with the uGMRT and a simultaneous observation with the SiFAP2 photometer installed at the TNG, constraining $\xi < 1.3 \times 10^2$, reporting the deepest UL in the optical band for this source.

Insight-HXMT observations, simultaneous with a radio burst detected by the SRT, set a punctual UL on the X-ray/radio efficiency η in the range of $\eta < (0.9 - 1.3) \times 10^7$ (1–30 keV band) depending on which emission model is used for the X-ray emission. Assuming the efficiency η is either 10^6 or 10^5 (with the latter being comparable to that of the SGR J1935+2154 event), we can estimate what the required simultaneous X-rays/radio observing time and X-ray burst fluence should be to reach a given detection probability, with the instrumentation available in our campaign. Assuming that the events follow a Poissonian statistics, for X-ray sensitivities in the range of $10^{-10} - 10^{-7} \text{ erg cm}^{-2}$, simultaneous X-ray/radio campaigns should last between $3 \times 10^2 - 3 \times 10^6$ hours for $\eta = 10^6$, or $6 \times 10^3 - 5 \times 10^7$ hours for $\eta = 10^5$. This result poses challenges in the detectability of a putative X-ray burst from this source. This can mainly be attributed to the cosmological nature of R3, being distant about 150 Mpc, $\sim 10^4$ times farther than the only source which to date has emitted an FRB-like signal simultaneous with an X-ray burst: SGR J1935+2154. Despite the existence of closer-by repeaters (e.g. FRB 20200120E, Kirsten et al. 2022; FRB 20181030A, Bhardwaj et al. 2021a), R3 represents at present a golden source for MWL follow-up for its periodic activity, high repetition rate and the relatively high energetic of the bursts.

Table 4.2: Properties of the detected bursts. The second column reports the barycentric time of arrival (TOA) infinite frequency (TDB units, DE405 ephemeris, TAI clock, DM-delay constant 2.41×10^{-16} s). The TOAs have been computed via the **Tempo2** software (Hobbs, Edwards, and Manchester, 2006). The third column is the activity phase ϕ obtained by folding the data at the period of 16.33 days and reference epoch of 58369.40 MJD (Pleunis et al., 2021). The fourth column reports the FWHM width Δt of the bursts. S , F , E and $\dot{\nu}$ are respectively the peak flux, the fluence and the isotropic energy of the bursts. The last column reports the linear drift rate $\dot{\nu}$ of the bursts (for the bursts for which it was not possible to assess this value, i. e. a drift was not present, a N.A. value is reported).

Burst ID	TOA (MJD)	ϕ	Δt (ms)	S (Jy)	F (Jy ms)	E (10^{37} erg)	$\dot{\nu}$ (MHz ms $^{-1}$)
SRT-P-01	59162.8253243218	0.5870	19 ± 2	3.1 ± 0.8	48 ± 16	8 ± 2.5	N.A.
SRT-P-02	59162.8343320911	0.5875	14.0 ± 0.5	12.2 ± 3.0	139 ± 43	24 ± 7	-9.7 ± 0.6
SRT-P-03	59162.8567440946	0.5889	13.2 ± 0.5	11.7 ± 2.9	125 ± 39	21 ± 6	-11.4 ± 0.6
SRT-P-04	59162.8665428914	0.5895	23 ± 2	3.2 ± 0.8	61 ± 20	10 ± 2	N.A.
SRT-P-05	59162.8752448474	0.5900	18 ± 2	5.3 ± 1.5	77 ± 29	13 ± 3	N.A.
	59162.8752449374	0.5900	23 ± 1	5.3 ± 1.5	98 ± 27	17 ± 3	N.A.
SRT-P-06	59162.9481096844	0.5945	14 ± 2	5.5 ± 1.4	62 ± 23	10 ± 6	N.A.
SRT-P-07	59162.9513861530	0.5947	23 ± 4	2.7 ± 0.7	50 ± 20	8 ± 1	N.A.
SRT-P-08	59162.9515615864	0.5947	20 ± 2	3.0 ± 0.7	49 ± 17	8 ± 1	N.A.
SRT-P-09	59162.9661486339	0.5956	12 ± 2	2.3 ± 0.6	22 ± 9	4 ± 3	N.A.
SRT-P-10	59194.7961833830	0.5448	9 ± 2	2.1 ± 0.6	15 ± 7	3 ± 1	N.A.
SRT-P-11	59244.9407380909	0.6155	22 ± 2	5.2 ± 1.3	92 ± 21	16 ± 2	-11.3 ± 0.6
SRT-P-12	59244.9503715983	0.6160	18.1 ± 0.9	11.8 ± 2.9	172 ± 55	29 ± 6	-10.7 ± 0.6
SRT-P-13	59244.9559004303	0.6164	12 ± 1	7.3 ± 1.9	70 ± 27	12 ± 3	N.A.
SRT-P-14	59258.8293625230	0.4660	16 ± 2	4.9 ± 1.3	64 ± 23	10 ± 2	N.A.
uGMRT-01	59441.0257263218	0.6231	20 ± 2	0.8 ± 0.2	8.9 ± 0.8	2.1 ± 0.2	-5.9 ± 0.5
uGMRT-02	59441.0453208005	0.6243	9.2 ± 0.7	0.6 ± 0.2	2.8 ± 0.9	0.3 ± 0.1	N.A.
uGMRT-03	59441.0575323455	0.6250	20.8 ± 0.6	7.9 ± 0.2	84 ± 3	36 ± 1	-10.5 ± 0.5
uGMRT-04	59441.0622128892	0.6254	7.6 ± 0.8	0.4 ± 0.4	2.5 ± 0.7	0.6 ± 0.1	N.A.
uGMRT-05	59441.0665624511	0.6256	6 ± 1	0.4 ± 0.1	0.6 ± 0.1	0.06 ± 0.01	N.A.
uGMRT-06	59441.0944839544	0.6273	16 ± 4	1.3 ± 1.2	7.9 ± 2.3	0.8 ± 0.2	N.A.
uGMRT-07	59441.1011067833	0.6277	15 ± 8	0.2 ± 0.1	0.9 ± 0.8	0.2 ± 0.2	N.A.

Summary and Conclusions

In this Thesis we have discussed several aspects of the Fast Radio Burst (FRB) astronomy and astrophysics. Here we make, after a quick introductory review, a summary, chapter by chapter, of the obtained results and then we draw our final conclusions and future outlooks.

Scientific Context

FRBs are ms-duration, narrow-band (hundreds of MHz), Jy-intensity, sporadic radio flashes coming from (mostly) outside our Galaxy, the origin of which is still largely unassessed.

Many models have been proposed to explain the FRBs. However, the FRBs brief durations, the $\sim 10^{40}$ erg burst energetics, and the $\sim 10^{36}$ K brightness temperatures strongly require models which invoke coherent emission scenarios. The so far most accredited models rely on a very compact object with a remarkably high magnetic field, such as a magnetar, as a main engine. The emission mechanism, in this context, can either be coming from the external regions of the magnetar magnetosphere, in a similar fashion to the pulsars, or from the shock generated by the interaction of some powerful outflow from the magnetar and the ambient medium, according to a scenario partially resembling that proposed for the Gamma-ray Bursts.

At the time of the writing of this work, a total of 625 FRB events were discovered. Most of them appear to be *una tantum* events, and only 25 FRB sources have shown a repeating behaviour, i.e. have emitted more than one burst (repeating FRBs, rFRBs). It is yet unclear if this dichotomy is real or whether all the FRBs are rFRBs. Furthermore, two of these rFRBs, FRB 20121102A and FRB 20180916B, showed to be periodically active (pFRBs), that is they are active for a certain window of time (about 90 and 5 days, respectively) and these activity windows happen cyclically with a period of about 160 days and 16 days, respectively.

The discovery of the rFRBs, and particularly of the pFRBs, has led to many progresses in the characterisation of these classes of the FRB population. FRB 20121102A appears to be very active (about 3400 bursts detected). It is capable to produce storms of bursts within hours, and with emission especially at the GHz frequencies (up to 8 GHz). It has been localised, with milliarcsecond precision, in the star-forming region of a dwarf galaxy distant about one Gpc. The presence of a co-located persistent radio source (PRS), the observation of significant variations in dispersion measure (DM) and the remarkably high value of the rotation measure (RM) point toward a very young compact object surrounded by a dense medium as the progenitor of FRB 20121102A.

In contrast with that, FRB 20180916B (with about 240 bursts detected) was localised in the outskirts of a spiral galaxy distant 149 Mpc, with no associated persistent PRS, showing that FRBs can inhabit very different host galaxies and local environments. Moreover, FRB 20180916B appears to be more active at lower frequencies (hundreds of MHz) rather than GHz frequencies. In addition, the emission frequency of the bursts from FRB 20180916B seems to follow a chromatic pattern, meaning that their frequency is dependent on the phase of the periodic cycle. In fact, bursts at L-band ($\sim$ GHz) tend to arrive at earlier phases than the bursts at P-band (a few hundreds of MHz), and the latter arrive earlier than the bursts at the LOFAR frequencies (150 MHz). As discussed by several authors, the presence of this chromatic activity favours single-body models, such as ultra long period magnetars or slowly free precessing magnetars, in the case of FRB 20180916B.

On April 2020, the Galactic Soft Gamma Repeater SGR J1935+2154 (a magnetar), went into an outburst phase, emitting a forest of X-ray bursts. In particular one of these bursts, detected by the satellites AGILE, *Insight*-HXMT, INTEGRAL and Konus/WIND, appeared to be simultaneous with a radio flash, detected by the radio telescopes CHIME and STARE2, and closely resembling a FRB. This multi-wavelength (MWL) detection, remarkably strengthened the link between magnetars and FRBs and strongly encouraged MWL campaigns on FRB sources. MWL campaigns in fact can be the key to constrain the progenitor and the emission mechanism(s) behind this enigmatic sources.

Chapter 1

After an initial review about the main phenomenological properties of the FRBs, in Chapter 1 we show how we have collected the whole dataset of the published time of arrivals (TOAs) of the bursts from both the periodic FRB 20121102A and the periodic FRB 20180916B, in order to carefully investigate the functional form $\nu_A = \nu_A(\phi)$ of a dependence, if any, between the phase ϕ of the periodic cycle and the central radio frequency ν_A of the observed bursts from the two sources, where ϕ was obtained by folding the aforementioned TOAs at the respective activity period.

We observed that, in contrast with the case of FRB 20180916B, **FRB 20121102A appears not to possess any obvious functional dependence** among the two quantities mentioned above. Our result, together with the evidence of an extreme environment of the source and its very long period of the cycle of activity, are suggestive that **orbital motion models are favoured in the case of FRB 20121102A**.

In addition, we noticed that the $\nu_A = \nu_A(\phi)$ dependence of FRB 20180916B can be well described with an exponential decay of the kind $\nu_A \propto e^{-\phi/\phi_c}$. The data have been fitted both with a frequentist and a Bayesian approach, obtaining agreeing results. No models predict such a specific behaviour so far and we did not try to introduce a new model to explain this pattern, leaving it as an additional phenomenological requirement for the future pFRB theoretical constructs.

Chapter 2

In Chapter 2 we first introduced the generalities about the techniques for performing the search for the FRBs. In doing so, we highlighted a problem related with the current use of very wide radio bands for undertaking these experiments.

In fact, current FRB searches are based on matched filtering techniques. The frequency averaged time series, obtained from an initial spectrogram, is then convolved with several trial top-hat functions and, if the signal-to-noise ratio S/N of one the convolved signals

exceeds a certain threshold, the candidates are saved. Modern backends of many radio telescopes (as it is the case of the Ultra Wideband Low receiver of Parkes), are starting to have remarkably large observational bandwidths (several GHz) thanks to the technological advances in electronics. However FRBs, being narrow-band events, would eventually have a small frequency occupancy in such receivers and the search of FRBs in time series obtained summing over the whole bandwidths could lead to sub-optimal outcomes. Therefore, sub-banded searches – i.e. searches for bursts in limited portions of the full available bandwidth – have been proposed and they appeared to be fruitful in literature, with the detection, for instance, of one burst from FRB 20190711A by looking to only a few dozen of MHz of bandwidth.

In this context, first we mathematically formalised these sub-banded searches. Unsurprisingly, if BW is the full observational bandwidth of the receiver and an FRB signal occupies a frequency region W_ν in it, **we showed that the sub-banded signal-to-noise ratio S/N^* , when searching for bursts in a sub-banded region overlapping the FRB signal, is related to the full-band S/N as: $S/N^* \sim \sqrt{BW/W_\nu} \times S/N$** . In contrast, if a FRB occupies the whole observational bandwidth, as it happens for relatively band-limited receivers, we showed that sub-banded searches lead to a S/N loss scaling as $\sim \sqrt{W_\nu/BW}$.

As a proof of concept, we reprocessed the high latitude portion of the High Time Resolution Universe (HTRU) survey carried on at Parkes, the observational bandwidth of which was ~ 400 MHz. Via a sub-banded search we detected 51 sub-banded FRB candidates, while easily redetecting the 10 previously found and published FRBs of this survey. In particular, 8 of the 10 redetected FRBs are extended in the full observational bandwidth and the sub-banded search produced candidates with sub-banded S/N^* lower than the full band S/N , with ratios among the two which are consistent with our predictions.

In order to assess the plausibility of the other detected candidates, we discussed how many candidates can arise by chance, due to random noise excesses in the data. We found that, by considering only candidates with $S/N > 10$, we should expect at most one false detection, due to a mere statistics of the noise. In view of the considerations above, we excluded all the lowest S/N candidates and concluded that only the 18 events with $S/N \geq 10$ should be considered as genuine candidates.

To summarise, **we plausibly detected 18 new bursts from the HTRU High Latitude survey**, almost twice the number of the previously detected bursts, showing that even for receivers with a bandwidth of only 400 MHz, sub-banded searches can be profitable.

Chapter 3

The first part of Chapter 3 was dedicated to a general description of the design of the radio telescopes used for the detection of FRBs. We then introduced the Northern Cross (NC) FRB Project, a program aiming to use the Medicina Northern Cross telescope as a modern FRB facility. The NC is located in Medicina (nearby Bologna, Italy) and it is T-shaped interferometer, built in 1967. In 2019 the NC underwent a refurbishment to make it capable to observe FRBs (among several other aims). The NC is a transit instrument which operates at 408 MHz with an observational bandwidth of 16 MHz. The two arms are aligned along the North-South (NS) direction and East-West direction (EW). At the current stage of the instrument renovation only a fraction of the NS arm (made of a total of 64 parabolic cylinders) is in use.

In the second part of Chapter 3, we presented the outcomes of our first FRB observational campaign at the NC. The campaign run from January 2020 to August 2021, and targeted four rFRB sources: 20180916B, 20181030A, 20200120E and 20201124A. From January 2020

until March 2021 we observed using six of the 64 reflective cylinders of the NS arm and from April 2021 until the end of the campaign we observed with eight reflective cylinders. The four FRB sources have been monitored according to the following timeline: FRB 280916B from the beginning until the end of the campaign (180 hours in total), FRB 20181030A from April 2020 until September 2020 (93 hours in total), FRB 20200120E from March 2021 until the campaign end (109 hours in total) and FRB 20201124A from April 2021 to June 2021 (68 hours in total).

Our main result was **the detection of three bursts from FRB 20180916B**, above a fluence threshold of 38 Jy ms. **These detections were the very first detections of a FRB source made by the NC telescope, and they represented a milestone for the facility.** We made a comparison with the results for the same source of the CHIME radio telescope. With this exercise, we inferred a total number of 2.7 ± 1.9 events expected at the NC during this campaign, consistent with our results.

We detected no bursts from the other sources. However, given the known rate of FRB 20201124A, we expected to detect 1.0 ± 1.1 bursts from this source, also consistent with our non detection.

Finally, we turned the non detections into a 95% confidence level lower limit on the slope α of the fluence distribution $N(> F) \propto F^{-\alpha+1}$ for the FRB 20181030A and 20200120E. The obtained constraints are $\alpha > 2.1$ and $\alpha > 2.2$, for FRB 20181030A and 20200120E, respectively.

Chapter 4

In Chapter 4 we first reviewed the MWL campaigns reported in the literature, with particular emphasis on the campaign which followed the SGR J1935+2154 event on April 2020.

Later, we described the results of our MWL campaign on FRB 20180916B, performed between October 2020 and August 2021, along eight activity cycles of the source. The campaign was led by the Sardinia Radio Telescope (SRT), observing with the dual-band receiver at 336 ± 40 MHz (P-band) and at 1547 ± 256 MHz (L-band), and by the upgraded Giant Metrewave Radio Telescope (uGMRT), observing at 400 ± 100 MHz. The SRT and the uGMRT telescopes were used in tandem with several optical telescopes: the Asiago (Galileo and Copernico) telescopes, CMO SAI MSU, CAHA 2.2m, RTT-150 and the Telescopio Nazionale Galileo (TNG). Several X-ray/ γ -ray satellites were as well shadowing the radio telescopes: AGILE, *Insight*-HXMT, INTEGRAL and Swift.

We detected 14 new bursts from this source with the SRT at P-band (SRT-P-01–14) and seven new bursts with the uGMRT (uGMRT-01–07). Neither the optical instruments nor the high-energy ones detected a plausible MWL counterpart. **A case of study was the observation of an optical peak within a window of 180 s around the burst SRT-P-02**, obtained with the Aqueye+ fast photometer, mounted at the Asiago/Copernicus telescope. Interestingly, the SRT-P-02 radio burst **happened to be the most energetic of the SRT series of the observing day of the 2020/11/09. However, the excess in the optical counts appears to be only slightly above a detection threshold** (for a 15 s time window) of 15 counts bins⁻¹, and below the threshold obtained by considering the full statistics of the observations: 18 counts bins⁻¹. **Thus there is not support to robustly tag the events as an optical counterpart to SRT-P-02.**

The strongest radio bursts (with MWL covering), SRT-P-02 (fluence ~ 139 Jy ms) and uGMRT-03 (fluence ~ 84 Jy ms), occurred while several instruments were covering the same portion of sky. In particular, SRT-P-02 was simultaneous with Asiago/Copernicus, CMO-SAI-MSU and *Insight*-HXMT observations, while uGMRT-03 was simultaneous with ob-

servations taken at Asiago/Copernicus and at TNG. These simultaneity allowed us to set **punctual upper limits (ULs)** on the FRB emission at other wavelengths by constraining the isotropic energy ratios at various bands. In particular, the simultaneous observations of uGMRT-03 with the SiFAP2 fast photometer mounted at the TNG set a punctual UL for the optical to radio isotropic energy ratio $\xi = E_{\text{optical}}/E_{\text{radio}} < 1.3 \times 10^2$, which is **the deepest UL for an optical FRB counterpart to date**.

Some magnetar models predict optical flashes, with duration of ~ 1 s, as result of blast waves in the magnetar surrounding medium, reaching $E_{\text{optical}} \sim 10^{44}$ erg. **If an event like that produces an FRB optical counterpart, it has to happen below the SiFAP2 UL of $E_{\text{optical}} < 2 \times 10^{42}$ erg (for a 1 s long optical counterpart)**.

The *Insight*-HMXT UL on SRT-P-02 provided a punctual UL for the X-ray to radio isotropic energy ratio of $\eta = E_{\text{X}}/E_{\text{radio}} < 10^7$, two orders of magnitude greater than the energy-ratio measured in the SGR J1935+2154 event, for which the two energies, in radio and X-ray, were both measured, giving a ratio $\eta \sim 10^5$. **Our punctual UL implies that, if an X-ray event occurred simultaneously to SRT-P-02, its energy should be less than 10^7 the energy of SRT-P-02**. It still remains challenging to constraint theoretical X-ray counterparts with this ratio. In fact, if we suppose that the ratio for extragalactic FRBs is similar to the SGR J1935+2154 case, this roughly implies that a radio burst about 10 times stronger (that is with fluence $> 10^3$ Jy ms) than the SRT-P-02 could further constrain this X-ray/radio efficiency η . This could be, however, extremely challenging to happen: by scaling the FRB 20180916B event rate reported by CHIME at the SRT P-band frequencies, a burst with a fluence above 10^3 Jy ms should happen (with a probability of the 99.9 %) after > 7000 hours.

Looking Ahead

The PhD work presented in this Thesis had many facets, revolving around the main goal of the detection of a non radio counterpart to a FRB.

As discussed in the Introduction, FRB MWL campaigns rely on the detection of radio bursts. To make this happen, the time on source is an asset and having dedicated FRB facilities is therefore necessary. Indeed, this is one of the ideas behind the Northern Cross FRB project. When the full North-South arm will be in place in the late 2023, in the case for instance of the FRB 20180916B, we will expect to detect more than ten times the number of bursts detected in the campaign described in this Thesis. In addition, we plan to follow more favourable repeating sources and Galactic magnetars with the purpose to be able to trigger MWL facilities in case of activity detected from these sources.

Sub-banded searches have proved to be fruitful, and detecting all the bursts contained in a given dataset could be crucial for a FRB MWL observation. Even if it may appear more likely to find a MWL counterpart simultaneously with a remarkably strong burst (hence weakening the purpose of a sub-banded search), we cannot completely discard other scenarios, where the putative optical/X-ray burst occur simultaneously with weaker radio bursts or even happening not simultaneously.

The work done in this Thesis formalises, in depth, the sub-banded searches, which will be essential to be performed when observations of FRBs will be carried out mostly with ultra-wide bandwidth receivers. It would be interesting, in the future, to also explore different strategies such as, for instance, spectro-temporal searches via two-dimensional matched filtering algorithms.

The MWL campaign on FRB 20180916B, despite setting the lowest optical upper limit for a FRB source to date thanks to the use of fast photometers, led again to a null detection

of a MWL counterpart. The principal cause of this can be ascribed to the fact that we are dealing with cosmological sources. FRB 20180916B, with its distance of 149 Mpc, is reasonably close to us and, furthermore, its periodic activity of only 16 days allows one to schedule several MWL campaigns in the typical time span of a scientific project. In contrast, FRB 20121102A with its 1 Gpc distance and its very long activity period makes it more cumbersome to organise large multi-telescope campaigns. The three other sources that we followed up with the Northern Cross are potentially interesting candidates for MWL campaigns, even though with some downsides: FRB 20181030A has one of the lowest known DMs, but it is fairly rarely active; FRB 20200120E is by far the closest FRB to us, but, probably due to its different origin, is quite faint; FRB 20201124A is farther than all of these, but has shown very intense activity phases during which some very strong bursts were recorded.

At the time of writing, no periodic activity has been found from any of these sources, forcing us for now to perform, in a similar fashion to what has been done with the SUPERB FRB 20140514A, follow-up searches triggered by a radio burst. The best strategy in these cases is to organise pre-approved target-of-opportunity observations at different telescopes and try to trigger them when the source is known to be active. In this respect, monitoring facilities, such as the Northern Cross, are crucial to notify the dedicated single-dish telescopes and the MWL facilities and timely activate the campaigns.

Regarding the future of the MWL campaigns, telescopes such as the Australian Square Kilometre Array Pathfinder (ASKAP), the MeerKAT radio telescope or the future Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) could be the real game changers in the quest for a MWL FRB: with their large Field-of-View and real-time capabilities of burst detection and localisation, they could be capable to trigger optical/high-energy observations within minutes, dramatically increasing the chances to eventually find a long sought and much hoped FRB panchromatic detection.

APPENDIX A

Appendix to Chap. 4: Observation Logs and Upper Limits

Table A.1: Log of the optical observations of FRB 20180916B carried out with Aqueye+ (Copernicus) and IFI+Iqueye (Galileo). The observations in bold are the ones in which a radio burst has been detected.

Camera	Observation ID	Start Time (topocentric) (UTC)	Duration (s)
Aqueye+ (Copernicus)	20201025-033103_gti1	2020-10-25 03:01:54.000	1748
	20201025-045249_gti1	2020-10-25 03:52:51.000	520
	20201109-200635	2020-11-09 19:06:36.000	7198
	20201109-221239_gti1	2020-11-09 21:26:00.000	2797.000
	20201109-231359	2020-11-09 22:14:00.000	8997
	20201110-020901	2020-11-10 01:09:02.000	1797
	20201110-024652	2020-11-10 01:46:53.000	897.000
	20201110-192232_gti1	2020-11-10 19:28:24.000	6848
	20201110-224746	2020-11-10 21:47:47.000	10798
	20201111-014901	2020-11-11 00:49:03.000	1798
	20201111-023825	2020-11-11 01:38:26.000	1198
	20201111-231309_gti1	2020-11-11 22:32:20.000	2050
	20201112-005752_gti1	2020-11-11 23:59:23.000	3508
	20201112-015938	2020-11-12 00:59:40.000	3598
	20201112-193512	2020-11-12 18:35:14.000	3598
	20201112-205147	2020-11-12 19:51:48.000	3597
	20201113-214903	2020-11-13 20:49:04.000	3597
	20210111-193142	2021-01-11 18:31:44.000	7981
	20210111-220228_gti1	2021-01-11 21:02:29.000	1950
	20210112-190452	2021-01-12 18:04:53.000	7197
	20210112-210529	2021-01-12 20:05:31.000	7198
	20210113-190245_gti1	2021-01-13 18:02:46.000	850
	20210113-210411_gti1	2021-01-13 20:04:13.000	1650
	20210113-210411_gti2	2021-01-13 20:34:13.000	2300
	20210114-183758_gti1	2021-01-14 17:43:49.000	5300
	20210813-232725	2021-08-13 21:27:26.000	7197
	20210814-012913	2021-08-13 23:29:14.000	7197
	20210814-234903	2021-08-14 21:49:04.000	7197
	20210815-014951	2021-08-14 23:49:53.000	7198
	20210815-035032	2021-08-15 01:50:34.000	898
	20210815-040612	2021-08-15 02:06:14.000	898
IFI+Iqueye (Galileo)	20201109-211141	59162 20:11:43.0	7197
	20201109-233529_gti1	59162 22:35:31.0	6850
	20201110-013640	59163 00:36:42.0	2697
	20201110-193505_gti1	59163 18:35:07.0	7700
	20201110-223616	59163 21:36:19.0	1797
	20201110-233217	59163 22:32:19.0	3597
	20210213-195451	59258 18:54:53.0	5398
	20210213-212539_gti1	59258 20:47:21.0	2897
	20210214-192834	59259 18:28:37.0	7197
	20210214-212932	59259 20:29:34.0	4197
	20210215-191649	59260 18:16:51.0	7197
	20210215-211741	59260 20:17:44.0	5397

Table A.2: Observation logs of CMO SAI MSU, RTT-150, CAHA 2.2m and TNG.

Camera	Start UT (topocentric)	Exposure (ks)
iXon 897 (CMO SAI MSU)	2020-11-09 17:31:00.0	3.84
	2020-11-09 19:18:00.0	29.28
	2020-11-10 17:42:00.0	24.48
iXon 888 (RTT-150)	2020-11-10 10:00:00.0	27.00
AstraLux (CAHA 2.2m)	2021-01-13 19:24:25.0	3.60
	2021-01-13 20:36:01.0	3.60
	2021-01-13 21:47:36.0	3.60
	2021-01-13 22:59:19.0	1.08
SiFAP2 (TNG)	2021-08-15 00:35:00.0	8.70

Table A.3: *AGILE* Coverage and MCAL upper limits (ULs) during the FRB 20180916B radio bursts. The second, third and fourth columns are the *AGILE* detectors in the FoV of the source. ULs (3σ) are evaluated on existing MCAL data acquisitions at the burst times, and correspond to a fluence of 33σ above the background; on the other hand, ULs (sub-ms) are evaluated in case no MCAL data acquisitions are present at the burst times (second column marked with a *), and refer to the UL fluence which would be required to issue a trigger in the sub-ms logic timescale.

Burst ID	MCAL	GRID	Super-A	UL (2σ) (erg cm $^{-2}$)	UL (sub-ms) (erg cm $^{-2}$)
SRT-P-01	NO	NO	NO	earth occultation	
SRT-P-02	NO	NO	NO	earth occultation	
SRT-P-03	YES*	NO	NO	1.1×10^{-6}	1.5×10^{-8}
SRT-P-04	YES*	YES	NO	1.3×10^{-6}	1.6×10^{-8}
SRT-P-05	YES*	NO	NO	1.9×10^{-6}	2.1×10^{-8}
SRT-P-06	NO	NO	NO	earth occultation	
SRT-P-07	NO	NO	NO	earth occultation	
SRT-P-08	NO	NO	NO	earth occultation	
SRT-P-09	YES*	NO	NO	1.5×10^{-6}	2.1×10^{-8}
SRT-P-10	YES*	NO	NO	1.4×10^{-6}	1.4×10^{-8}
SRT-P-11	YES	NO	NO	1.9×10^{-6}	2.0×10^{-8}
SRT-P-12	NO	NO	NO	idle mode	
SRT-P-13	YES*	NO	NO	1.6×10^{-6}	1.6×10^{-8}
SRT-P-14	YES*	NO	NO	1.3×10^{-6}	1.5×10^{-8}
uGMRT-01	YES	NO	NO	1.7×10^{-6}	1.2×10^{-8}
uGMRT-02	NO	NO	NO	earth occultation	
uGMRT-03	NO	NO	NO	earth occultation	
uGMRT-04	NO	NO	NO	idle mode	
uGMRT-05	NO	NO	NO	idle mode	
uGMRT-06	YES	NO	NO	7.2×10^{-6}	5.9×10^{-8}
uGMRT-07	YES	NO	NO	1.3×10^{-6}	1.2×10^{-8}

Table A.4: *Insight*–HXMT observation log. The first column reports the *Insight*–HXMT observation ID, the second and third columns the observation start and stop time (topocentric) and the last three columns the on-source exposure time for the three satellite’s instruments.

Obs ID	Start UT	End UT	LE (ks)	ME (ks)	HE (ks)
P0303077001	2020-10-23 17:21:49	2020-10-24 01:29:27	11.1	12.7	7.9
P0303077002	2020-10-24 17:12:47	2020-10-25 01:19:58	11.7	12.3	7.9
P0303077003	2020-11-09 16:29:24	2020-11-10 00:36:49	14.1	11.6	4.4
P0303077004	2020-11-10 16:21:02	2020-11-11 00:29:44	14.9	12.1	6.9
P0303077005	2021-01-12 16:55:51	2021-01-13 01:12:32	11.2	12.3	10.3
P0303077007	2021-01-13 16:46:54	2021-01-14 00:53:14	11.0	12.3	11.0
P0403084001	2021-08-13 19:37:53	2021-08-15 02:10:55	53.5	45.5	31.9

Table A.5: INTEGRAL observation log. The first and second column report the observation start and stop time (topocentric), the third column the pointing ID number and the last column the exposure time.

Start Time (UTC)	Stop Time (UTC)	Pointing ID	On-source Time (ks)
2020-12-18 21:42	2020-12-18 22:12	231000350010 - 231000380010	7.2
2020-12-19 00:23	2020-12-19 00:53	231000400010 - 231000400010	1.8
2020-12-19 01:27	2020-12-19 01:57	231000420010 - 231000540010	23.3
2020-12-21 08:39	2020-12-21 09:09	231100250010 - 231100280010	7.2
2020-12-21 11:38	2020-12-21 12:08	231100310010 - 231100540010	43.1
2020-12-24 05:56	2020-12-24 06:26	231200350010 - 231200380010	7.2
2020-12-24 08:36	2020-12-24 09:06	231200400010 - 231200440010	9.0
2020-12-27 08:13	2020-12-27 08:44	231300540010 - 231300560010	7.1
2020-12-27 10:52	2020-12-27 11:21	231300580010 - 231300780010	37.7
2020-12-28 06:29	2020-12-28 06:59	231300950010 - 231301010010	12.6
2020-12-30 13:29	2020-12-30 13:59	231400810010 - 231400820010	3.6
2020-12-30 15:23	2020-12-30 15:53	231400850010 - 231401040010	35.9
2021-01-01 02:33	2021-01-01 03:03	231500300010 - 231500360010	12.6
2021-01-03 20:01	2021-01-03 20:31	231600330010 - 231600360010	7.2
2021-01-03 22:42	2021-01-03 23:12	231600380010 - 231600520010	27.0
2021-01-05 19:28	2021-01-05 19:59	231700020010 - 231700060010	9.1
2021-01-12 06:55	2021-01-12 07:21	231900540010 - 231900740010	70.9
2021-01-13 03:48	2021-01-13 04:45	231900750010 - 231900800010	20.9
2021-01-15 00:01	2021-01-15 01:26	232000340010 - 232000580010	88.4
2021-01-16 11:21	2021-01-16 11:51	232100030010 - 232100200010	32.4
2021-01-16 22:03	2021-01-16 22:33	232100230010 - 232100230010	1.8
2021-01-17 01:01	2021-01-17 01:31	232100290010 - 232100300010	3.6
2021-01-22 17:44	2021-01-22 18:25	232300480010 - 232300710010	61.4
2021-01-23 13:02	2021-01-23 13:32	232300750010 - 232300800010	10.8
2021-01-23 18:22	2021-01-23 18:52	232300850010 - 232300890010	9.0
2021-01-24 00:15	2021-01-24 00:45	232300960010 - 232300960010	1.8
2021-02-14 17:03	2021-02-14 18:01	233200020010 - 233200240010	84.3
2021-02-15 17:29	2021-02-15 18:27	233200260010 - 233200300010	21.7

Table A.6: INTEGRAL fluence ULs. The second column is the ID of the Science Window Data catalogue, the third column contains the off-axis angles the fourth column contains the ULs for each burst, as discussed in 4.4.3.

Burst ID	ScW ID	θ, φ (deg.)	UL (erg cm ⁻² s ⁻¹)
SRT-P-01	229500410010	156.4, -159.4	4.8×10^{-7}
SRT-P-02	229500410010	156.4, -159.4	4.2×10^{-7}
SRT-P-03	229500420010	156.0, -155.3	5.2×10^{-7}
SRT-P-04	229500420010	156.0, -155.3	4.6×10^{-7}
SRT-P-05	229500420010	156.0, -155.3	5.3×10^{-7}
SRT-P-06	229500440010	154.3, -160.2	4.9×10^{-7}
SRT-P-07	229500440010	154.3, -160.2	4.1×10^{-7}
SRT-P-08	229500440010	154.3, -160.2	5.6×10^{-7}
SRT-P-09	229500440010	154.3, -160.2	3.8×10^{-7}
SRT-P-10	230700380010	117.1, 147.8	4.3×10^{-7}
SRT-P-11	232600520010	118.7, -118.3	5.5×10^{-7}
SRT-P-12	232600530010	118.7, -118.3	4.8×10^{-7}
SRT-P-13	232600530010	118.7, -118.3	3.7×10^{-7}
SRT-P-14	233100630010	50.7, -70.8	1.3×10^{-7}
uGMRT-01	240000130010	75.6, 93.6	2.0×10^{-7}
uGMRT-02	240000130010	75.6, 93.6	1.1×10^{-7}
uGMRT-03	240000140010	73.4, 94.2	1.8×10^{-7}
uGMRT-04	240000140010	73.4, 94.2	1.5×10^{-7}
uGMRT-05	240000140010	73.4, 94.2	1.4×10^{-7}
uGMRT-06	240000150021	73.1, 95.0	2.4×10^{-7}
uGMRT-07	240000150021	73.1, 95.0	1.5×10^{-7}

Table A.7: Swift Coverage and ULs. The first column is the starting time of the observation (both topocentric), the second column is the stopping time and the third column is the 0.3–10 keV X-ray flux UL.

Start Time	Stop Time	UL (erg cm ⁻² s ⁻¹)
2020-10-22 05:33:59	2020-10-27 18:09:56	3.0×10^{-13}
2020-11-08 17:16:50	2020-11-12 15:31:56	2.7×10^{-13}
2020-12-09 04:06:58	2020-12-15 11:34:56	3.7×10^{-13}
2020-12-30 18:17:55	2021-01-01 11:49:56	4.3×10^{-13}
2021-01-10 02:40:33	2021-01-16 02:25:56	2.6×10^{-13}
2021-01-29 16:25:31	2021-02-02 16:25:55	3.1×10^{-13}
2021-03-02 13:27:42	2021-03-06 14:34:56	3.0×10^{-13}
2021-03-17 13:16:26	2021-03-23 15:57:56	2.6×10^{-13}
2021-04-19 12:02:25	2021-04-25 11:26:56	2.6×10^{-13}
2021-05-09 09:21:59	2021-05-14 10:40:56	3.3×10^{-13}
2021-05-24 09:11:17	2021-05-25 10:49:56	6.8×10^{-13}
2021-06-07 08:07:52	2021-06-13 07:48:56	2.7×10^{-13}
2021-06-22 04:47:04	2021-06-28 07:17:56	2.5×10^{-13}
2021-07-08 06:05:06	2021-07-14 07:12:56	3.4×10^{-13}
2021-07-25 04:47:26	2021-07-31 10:47:56	3.0×10^{-13}

Table A.8: *Insight*-HXMT high-energy ULs for the six FRBs that were observed. The last column report the 2σ Gaussian Confidence Level (CL).

Burst ID	Spectral Model ^(a)	Time Interval ^(b) (s)	Bin (ms)	UL (1-30 keV) $10^{-10} \text{ erg cm}^{-2}$	CL (2σ)
SRT-P-01	PL $\Gamma = 2$	$[-16, +100]$	1	1.6	2.8
SRT-P-01	PL $\Gamma = 2$	$[-16, +100]$	16	2.7	2.5
SRT-P-01	PL $\Gamma = 2$	$[-16, +100]$	128	6.6	3.0
SRT-P-01	OTTB $kT = 50 \text{ keV}$	$[-16, +100]$	1	2.2	2.8
SRT-P-01	OTTB $kT = 50 \text{ keV}$	$[-16, +100]$	16	3.9	2.5
SRT-P-01	OTTB $kT = 50 \text{ keV}$	$[-16, +100]$	128	9.5	3.0
SRT-P-01	OTTB $kT = 200 \text{ keV}$	$[-16, +100]$	1	2.3	2.8
SRT-P-01	OTTB $kT = 200 \text{ keV}$	$[-16, +100]$	16	4.1	2.5
SRT-P-01	OTTB $kT = 200 \text{ keV}$	$[-16, +100]$	128	9.9	3.0
SRT-P-02	PL $\Gamma = 2$	$[-100, +100]$	1	2.0	3.0
SRT-P-02	PL $\Gamma = 2$	$[-100, +100]$	16	3.5	3.6
SRT-P-02	PL $\Gamma = 2$	$[-100, +100]$	128	7.8	2.9
SRT-P-02	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	1	2.8	3.0
SRT-P-02	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	16	5.0	3.6
SRT-P-02	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	128	11	2.9
SRT-P-02	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	1	2.9	3.0
SRT-P-02	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	16	5.2	3.6
SRT-P-02	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	128	12	2.9
SRT-P-07	PL $\Gamma = 2$	$[-36, +100]$	1	1.6	3.2
SRT-P-07	PL $\Gamma = 2$	$[-36, +100]$	16	2.7	3.3
SRT-P-07	PL $\Gamma = 2$	$[-36, +100]$	128	5.5	3.0
SRT-P-07	OTTB $kT = 50 \text{ keV}$	$[-36, +100]$	1	2.2	3.2
SRT-P-07	OTTB $kT = 50 \text{ keV}$	$[-36, +100]$	16	3.9	3.3
SRT-P-07	OTTB $kT = 50 \text{ keV}$	$[-36, +100]$	128	7.8	3.0
SRT-P-07	OTTB $kT = 200 \text{ keV}$	$[-36, +100]$	1	2.3	3.2
SRT-P-07	OTTB $kT = 200 \text{ keV}$	$[-36, +100]$	16	4.1	3.3
SRT-P-07	OTTB $kT = 200 \text{ keV}$	$[-36, +100]$	128	8.2	3.0
SRT-P-08	PL $\Gamma = 2$	$[-51, +100]$	1	1.6	3.1
SRT-P-08	PL $\Gamma = 2$	$[-51, +100]$	16	2.7	3.2
SRT-P-08	PL $\Gamma = 2$	$[-51, +100]$	128	5.5	2.9
SRT-P-08	OTTB $kT = 50 \text{ keV}$	$[-51, +100]$	1	2.2	3.1
SRT-P-08	OTTB $kT = 50 \text{ keV}$	$[-51, +100]$	16	3.9	3.2
SRT-P-08	OTTB $kT = 50 \text{ keV}$	$[-51, +100]$	128	7.8	2.9
SRT-P-08	OTTB $kT = 200 \text{ keV}$	$[-51, +100]$	1	2.3	3.1
SRT-P-08	OTTB $kT = 200 \text{ keV}$	$[-51, +100]$	16	4.1	3.2
SRT-P-08	OTTB $kT = 200 \text{ keV}$	$[-51, +100]$	128	8.2	2.9

(a) PL: power-law with photon index $\Gamma = 2$; OTTB: optically thin thermal bremsstrahlung.

(b) TDB since FRB time calculated at infinite frequency.

Continue of Tab. A.8.

Burst ID	Spectral Model ^(a)	Time Interval ^(b) (s)	Bin (ms)	UL (1-30 keV) $10^{-10} \text{ erg cm}^{-2}$	CL (2σ)
SRT-P-09	PL $\Gamma = 2$	$[-100, +100]$	1	1.6	2.5
SRT-P-09	PL $\Gamma = 2$	$[-100, +100]$	16	3.1	3.0
SRT-P-09	PL $\Gamma = 2$	$[-100, +100]$	128	7.0	2.9
SRT-P-09	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	1	2.2	2.5
SRT-P-09	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	16	4.5	3.0
SRT-P-09	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	128	10	2.9
SRT-P-09	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	1	2.3	2.5
SRT-P-09	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	16	4.6	3.0
SRT-P-09	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	128	11	2.9
uGMRT-01	PL $\Gamma = 2$	$[-100, +100]$	1	$1.6(3.6)^{(c)}$	2.7
uGMRT-01	PL $\Gamma = 2$	$[-100, +100]$	16	$3.1(8.7)^{(c)}$	3.4
uGMRT-01	PL $\Gamma = 2$	$[-100, +100]$	128	$6.6(30)^{(c)}$	3.3
uGMRT-01	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	1	$2.2(6.8)^{(c)}$	2.7
uGMRT-01	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	16	$4.5(16)^{(c)}$	3.4
uGMRT-01	OTTB $kT = 50 \text{ keV}$	$[-100, +100]$	128	$9.5(56)^{(c)}$	3.3
uGMRT-01	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	1	$2.3(12)^{(c)}$	2.7
uGMRT-01	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	16	$4.6(29)^{(c)}$	3.4
uGMRT-01	OTTB $kT = 200 \text{ keV}$	$[-100, +100]$	128	$11(97)^{(c)}$	3.3
uGMRT-02	PL $\Gamma = 2$	$[-100, +27.7]$	1	$2.4^{(d)}$	2.6
uGMRT-02	PL $\Gamma = 2$	$[-100, +27.7]$	16	$4.7^{(d)}$	3.1
uGMRT-02	PL $\Gamma = 2$	$[-100, +27.7]$	128	$11.^{(d)}$	2.9
uGMRT-02	OTTB $kT = 50 \text{ keV}$	$[-100, +27.7]$	1	$2.6^{(d)}$	2.6
uGMRT-02	OTTB $kT = 50 \text{ keV}$	$[-100, +27.7]$	16	$5.1^{(d)}$	3.1
uGMRT-02	OTTB $kT = 50 \text{ keV}$	$[-100, +27.7]$	128	$12.^{(d)}$	2.9
uGMRT-02	OTTB $kT = 200 \text{ keV}$	$[-100, +27.7]$	1	$2.6^{(d)}$	2.6
uGMRT-02	OTTB $kT = 200 \text{ keV}$	$[-100, +27.7]$	16	$5.3^{(d)}$	3.1
uGMRT-02	OTTB $kT = 200 \text{ keV}$	$[-100, +27.7]$	128	$12^{(d)}$	2.9

(a) PL: power-law with photon index $\Gamma = 2$; OTTB: optically thin thermal bremsstrahlung.

(b) TDB since FRB time calculated at infinite frequency.

(c) Values among parentheses refer to the 1–100 keV passband.

(d) Values refer to the 10–30 keV passband.

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