Long Wavelength Astrophysics

by

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Abstract

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Chapter 1

Introduction

The most interesting advances in science come not from concerted efforts to answer specific questions, but rather from exploring a previously unplumbed parameter space. The father of observational astronomy, Galileo, did not construct Lippershey's telescope in order to discover the Jovian satellites. Instead, he used a novel tool to investigate suprahuman magnitudes and spatial resolution to observe three moons "totally invisible by their smallness" orbiting Jupiter (Drake, 1978). The tradition has continued in the centuries since, particularly in astrophysics where we humans have no innate intuition; by definition everything we study is outside of this world. Pulsars, for example, were discovered accidentally with a radio telescope that was built to study interstellar scintillation in quasars. Dark matter and dark energy are two more examples of largely unpredicted, major discoveries. A more recent uncovered phenomenon is fast radio bursts (FRBs), which are a primary focus of this thesis. Their discovery was the result of searching dispersion measure (DM) space at high time resolution.

1.1 Digital Telescopes

A telescope's primary purpose is to provide for us spatial, temporal, and chromatic information about electromagnetic fields on the sky. Mathematically, telescopes first perform a spatial Fourier transform (from **x**- to **k**-modes), traditionally with a mirror or reflector, and then another Fourier transform in time (from τ to ν) to separate the signal by wavelength, with, e.g., a diffraction grating. The electromagnetic wave's modulus is typically then squared, destroying phase information, whether with a bolometer or a charge-coupled device (CCD). Modern radio telescopes carry out a similar set of steps, except they use powerful computers in place analog instrumentation. They also have the ability to preserve phase information by measuring a quantity proportional to the electric field, namely voltage.

In an era when electric fields can effectively be sampled billions of times per second, radio telescopes are becoming almost entirely digital. While the cost of constructing large single-dish telescopes is not expected to decrease substantially, the cost of building large computing clusters is, which makes it economically and strategically sensible to point one's telescope and channelize in software.

1.2 Time-domain Sky

1.2.1 Propagation effects

Cold plasma dispersion

Electromagnetic waves traveling through a cold dense plasma will undergo dispersion. Here, "cold" refers to the condition that the thermal velocity of the particles in the plasma is much less than that of the wave, i.e.,

$$v_p \gg v_{ion} = \sqrt{2\, k_B T / m_{ion}}. \tag{1.1}$$

The dispersion results in a frequency-dependent group velocity caused by differential refractive index in an ionized plasma. The refractive index is given by,

$$n = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}, \tag{1.2}$$

where ω_p is the plasma's resonant frequency and ω is the electromagnetic wave's frequency. The plasma frequency is

$$\omega_p = \sqrt{\frac{n_e e^2}{4\pi^2 m\, c}}, \tag{1.3}$$

using e, n_e, and m as the electron charge, number density, and mass respectively. Plugging this plasma frequency relation into equation 1.2 and expanding about n_e, we get,

$$v_g = c\left(1 - \frac{n_e e^2\, \lambda^2}{2\pi m c^2}\right). \tag{1.4}$$

This equation holds for most of the physics described in this thesis, since the dispersive electron plasmas in the IGM, ISM, and even in supernovae (SNe) remnants are relatively diffuse, with plasma frequencies well below the bands in which we observe. For reference, typical values are $n_e^{IGM} \sim 10^{-7}$ cm^{-3} (Madau, 2000), $n_e^{ISM} \sim 10^{-2}$ cm^{-3} (Lyne & Graham-Smith, 1998) in our Galaxy, and in $n_e^{SNe} \sim 10^{1-3}$ cm^{-3} in remnants.

For a single pulse, the light travel-time, t, can be written as the integral, $\int_0^D \mathrm{d}l/v_g$, into which we can plug Eq. 1.4. The frequency-dependent time delay is then,

$$\Delta t = t - \frac{D}{c} \tag{1.5}$$

$$= 1.345 \times 10^{-3}\, \nu^{-2} \int_0^D n_e\, \mathrm{d}l \ \text{ seconds.} \tag{1.6}$$

Here we have switched from angular frequency, ω, to ν in Hz. Dispersion measure (DM) can then be defined as,

$$\mathrm{DM} \equiv \int_0^D n_e\, \mathrm{d}l, \tag{1.7}$$

which is just an electron column density, and is usually reported in units pc cm^{-3}. For a telescope observing between ν_b and ν_t in GHz, the arrival-time difference between the top and bottom of the band will be,

$$\Delta t_{b,t} = 4.15 \times 10^{-3} \, \mathrm{DM} \left(\nu_b^{-2} - \nu_t^{-2} \right) \text{ seconds.} \tag{1.8}$$

While this effect delays all waves with $\nu > \nu_p$, (waves below the plasma frequency will decay exponentially and will not propagate) it is only observationally important for switch sources. Typical pulsars in our Galaxy have DMs between 10-100 pc cm^{-3}, while FRB DMs can be as high as 2000 pc cm^{-3}. The latter gives a dispersion delay of nearly forty seconds between 400 MHz and 800 MHz, where CHIME will observe.

Faraday rotation

If a cold plasma also has a magnetic field, a propagating electromagnetic wave's plane of polarization will be rotated. This is called the "Faraday effect" or "Faraday rotation", named after the nineteenth century English physicist (Faraday & Martin, 1936). The rotation is caused by circular birefringence, meaning left- and right-circularly polarized light travel at slightly different speeds. Since linear polarization can be thought of as the superposition of a right- and left-handed wave, the result is a rotation of the linear polarization vector.

Like dispersion, this effect is chromatic, depending quadratically on wavelength. The linear polarization vector will be rotated by

$$\phi = 2\mathrm{RM}\lambda^2 \tag{1.9}$$

where RM is "rotation measure" with units rad m^{-2}. The extent of this rotation depends on the projection of the magnetic field onto the direction of propagation as follows,

$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^L n_e(l) B_{\parallel}(l) dl. \tag{1.10}$$

Here $B_{\parallel}$ is the component of the magnetic field vector parallel to $\mathrm{d}\vec{l}$. RM can be thought of as an electron-density-weighted mean value of the line-of-site magnetic field between the observer and the source. Conventionally, it is positive for fields directed towards the observer (Manchester & Taylor, 1977).

By dividing Eq. 1.10 by Eq. 1.7 and assuming n_e is roughly constant in whatever medium the radio waves are traversing, one can estimate the average magnetic field in that direction. The ratio of RM to DM is then,

$$\frac{\mathrm{RM}}{\mathrm{DM}} = \frac{e^3}{2\pi m^2 c^4} \frac{\int_0^L n_e(l) B_{\parallel}(l) dl}{\int_0^L n_e(l) dl} = 0.81 \left\langle B_{\parallel} \right\rangle \ \mu G. \tag{1.11}$$

This is a useful tool for understanding the ISM and the structure of the Milky Way's magnetic field.

Scattering

The least understood propagation effect in ionized astrophysical plasma is scattering. Scattered radio waves self-interfere constructively and destructively to produce intensity fluctuations (scintillation), temporal broadening, and angular broadening (Manchester & Taylor, 1977). The cause of this multi-path propagation is still greatly contested (Goldreich & Sridhar, 2006; Pen & Levin, 2014). It was assumed to be due to Kolmogorov turbulence, from which one could easily derive the frequency scalings of temporal scattering ($\tau \propto \nu^{-4}$) and angular broadening ($\theta \propto \nu^{-2}$) (Rickett, 1977). Recently, however, this picture has been called into question by pulsar scintillation observations. Stinebring et al. (2001) found parabolic arclets in Fourier-transformed "dynamic spectra" (a 2D time/frequency field) for a number of pulsars, implying that scattering occurs in just one or two screens and occurs in localized clumps.

Irrespective of the underlying physics, scattering is well-studied phenomenologically. It provides a useful tool not just for studying the ISM, but also for FRB observation. We discuss this both in Sect. 1.3 and Chapter ??.

1.3 Fast Radio Bursts

The discovery of fast radio bursts has captivated the attention of astronomers for two reasons: their origin is a genuine mystery, the likes of which had not been seen in transient astrophysics in decades; and the problem appears to be tractable on timescales of years to a decade. There is good reason to think that with the right survey one could at least determine their radial distribution, as well as the nature of the burst source, if not specific details. This is not true of other major contemporary questions. The tensor-to-scalar ratio, r, in inflationary cosmology, or the deviation of dark energy's w from -1, could be constrained with arbitrary improvements without ever making a detection.

The first FRB was discovered in 2007 by Lorimer et al. (2007), and has since been called the "Lorimer Burst". Its Galactic latitude ($b = -41.8°$) and large dispersion measure (DM$=$ 375 pc cm^{-3}) implied that the $\sim$10 millisecond burst was extragalactic (Lorimer et al., 2007). However, in the years immediately following, no fast transients were seen with DMs exceeding the expected Galactic contribution. This lead to skepticism about the celestial nature of the Lorimer Burst and suspicion that it was terrestrial interference (Burke-Spolaor et al., 2011).

Suspicion that this was a one-off event was relinquished with the discovery of four more FRBs in 2010 in the High Time Resolution Universe (HTRU) survey (Thornton et al., 2013). Based on the 23 days of observing with a 0.55 deg^2 beam, they reported a surprisingly large rate of $\sim 10^4$ events sky^{-1} day^{-1}. Though their detection made a much stronger case for the extraterrestrial nature of FRBs, it was not unequivocally accepted. This is because until the discovery of FRB 121102 in Arecibo's Pulsar ALFA

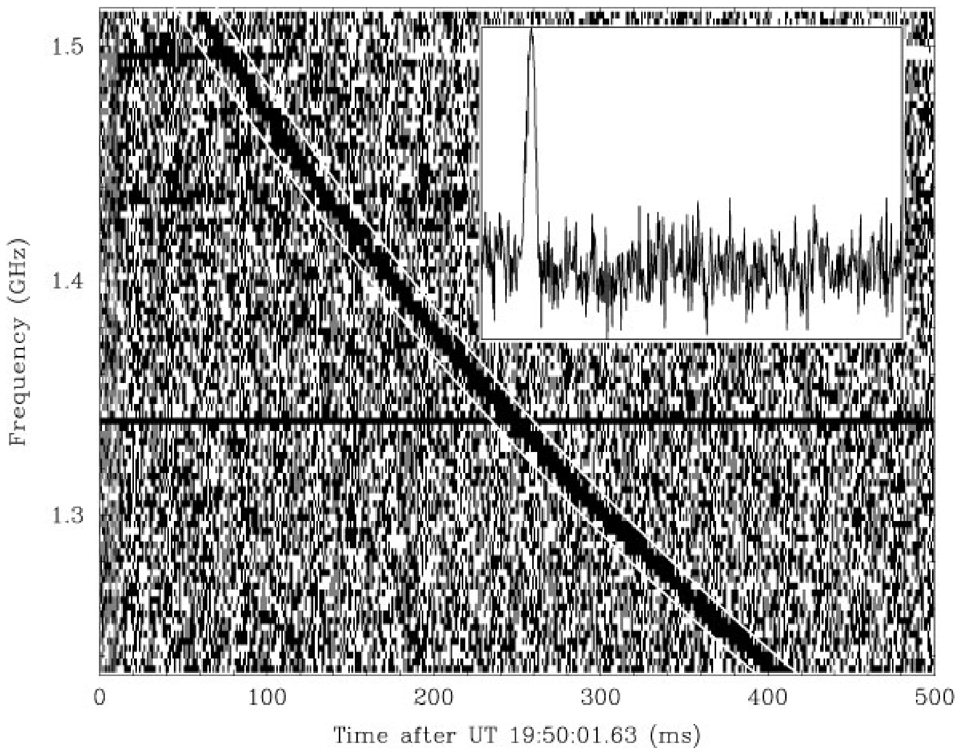

Figure 1.1: Figure reproduced from (Lorimer et al., 2007) of the so-called Lorimer Burst, which is the first known FRB.

(PALFA) survey, all FRBs had been found with the Parkes radio telescope and in its 13-beam receiver. At Parkes, an unexplained "class" of transients were found in high time resolution data that appeared to be dispersed with hundreds of pc cm^{-3}, and which lasted for ten to a few hundred milliseconds (Burke-Spolaor et al., 2011; Bagchi et al., 2012). These pulses were given the name "Perytons", named after a mythological hybrid animal.

While an astronomical origin for Perytons was excluded early on due to their multi-beam detections, it was not obvious if they were being emitted in the earth's atmosphere naturally, or by something human-made (Katz, 2014; Dodin & Fisch, 2014; Danish Khan, 2014). It was later found by Petroff et al. (2015d) that Perytons were likely caused by an on-site microwave oven. The microwave's magnetron was found to mimic the sweeping λ^2 dependence of truly dispersed sources when the oven's door was opened prematurely (Petroff et al., 2015d). This made sense given the preponderance of events around local noon, i.e. lunchtime.

In the years since Thornton et al. (2013) discovered their four HTRU bursts, a dozen or so more have been found. These are cataloged online at FRBCAT[1] (Petroff et al., 2016). As we have mentioned, Arecibo's detection of FRB 121102 ensured that the events were not Parkes-specific. Petroff et al. (2015a) found the first FRB in real-time, as well as the first burst for which there was polarization information. FRB 110523 (Masui et al., 2015) was found in archival data from the Green Bank Telescope (GBT) intensity mapping experiment, which fortuitously saved its data with millisecond time resolution even though it was not strictly necessary for their cosmology. The completed HTRU survey also provided five new sources, found by Champion et al. (2016).

With nearly two dozen detected at the time of this writing, there is still no agreed-upon definition of an FRB. They appear to last for ∼milliseconds, have dispersion measures that are ≥2.5 times that of the Galactic contribution (the range has been $375-1600$ pc cm^{-3}), and maximum flux densities of roughly a Jansky. Exceptions include the Lorimer Burst, which was ∼30 Jy and is the brightest FRB by far, and 010621 whose DM was only about 1.4 times that expected from the Milky Way (Lorimer et al., 2007; Keane et al., 2012). At both L-band and ∼800 MHz, a detectable rate of several thousand each day over the whole sky now seems likely (Connor et al., 2016a; Champion et al., 2016).

And such ranges are known to be incomplete. Brightness is reported as if the burst were found at the beam's center, so each published flux is a lower limit. We also do not yet know the DM distribution. There may be a population of events with DM $\approx 10^4$ pc cm^{-3} that are either too rare to see in two dozen bursts, or to which current search

[1] http://www.astronomy.swin.edu.au/pulsar/frbcat/

algorithms have not been sensitive. Scattering is another poorly constrained parameter. FRBCAT lists five bursts with evidence for scattering, with broadening index around -4, as one would expect (Petroff et al., 2016). However, several sources have been unresolved in time, meaning their width and scattering properties are only constrained from above. The extent and prevalence of scattering is of interest for a couple reasons. One is that it has implications for the source environment, and also because scattering is the limiting factor for low-frequency surveys, like CHIME and LOFAR (Bandura, 2014; van Leeuwen, 2014); an FRB scattered to 10 ms at 1.4 GHz would be several seconds at 400 MHz and effectively undetectable.

1.3.1 Models

Starting with the Lorimer Burst and continuing on to the four high-lat HTRU FRBs, the default assumption was that the progenitors were at cosmological distances (i.e. IGM-induced dispersion). To a lesser extent, the community seemed to assume they did not repeat, in part because of null-result follow up observations that were done (Petroff et al., 2015c), but also because bursts coming from gigaparsec distances might only have enough energy for a single event. It has been argued (Katz, 2016) that the cosmological interpretation is the most economical way of getting such large column densities of free electrons. In reality, up until recently we did not know their radial distance to better than five orders of magnitude. This is because with such a small sample of events, there was no way of knowing whether they were coming from $z \approx 0.5$, from within our Galaxy, or from our atmosphere.

A significant fraction of this thesis will focus on theoretical elements regarding fast radio bursts. Therefore it would be prudent to provide context for both the history of models that have come in and out of the picture, as well as a time-line of the observations that have informed them. We will start by enumerating the most prevalent theoretical explanations for the origin of FRBs. They will be lumped into two categories: cataclysmic, in which the progenitor is effectively destroyed, and non-cataclysmic. Note that in chapter **??** table **??** partitions models by their distance and includes each theory's predictions for various observables.

Cataclysmic explanations

- *Blitzars:* Falcke & Rezzolla (2014) suggested that a supramassive neutron star might emit a burst of radio once it has lost its angular momentum and has begun to collapse into a black hole. This collapse will hide the star behind the event horizon and magnetic field lines will snap into place. In this model FRBs do not repeat, since the radio chirp is the object's final signal. The authors also assume these compact objects would be at cosmological distances. Given the known existence of neutron stars with mass greater than the Chandrasekhar limit, Falcke & Rezzolla (2014) conjectured that a few percent of neutron stars are supramassive and rotationally supported, and thereby eventually undergo such a transition. A natural shortcoming of this model is its lack of testable predictions. No electromagnetic counterpart is to be expected, and the proposed gravitational wave counterpart would likely be quite weak.

- *Merging compact objects:* The timescales and energies involved invoke merging compact objects. It has been suggested that NS-NS mergers similar to short-GRBs would satisfy the energetics (Totani, 2013). One might then expect a gamma-ray counterpart. Merging white dwarfs has also been proposed (Kashiyama et al., 2013). It has been suggested that the event rates may not be high enough in these models.

- *Evaporating black holes:* In this model exploding primordial black holes emit energy at wavelengths corresponding to their Schwarzschild radius, which Barrau et al.

(2014) suggest The relation,

$$\lambda_{obs} \propto (1+z) \left(\sinh^{-1} \left[\left(\frac{\Omega_\Lambda}{\Omega_M} \right)^{0.5} (1+z)^{-3/2} \right] \right)^{1/4}, \tag{1.12}$$

gives observable wavelengths of ∼centimeters.

Non-cataclysmic explanations

- *Galactic flare stars:* One of the first non-cosmological, non-cataclysmic models for FRBs suggested they were flaring main-sequence stars in our own Galaxy (Loeb et al., 2014). In this scenario, coronal plasma provides the DM rather than the IGM. The authors argue that the heightened energetics required by FRBs at cosmological distances theoretically motivates nearby sources. The model generically predicts repetition and, of course, overlap with known Galactic variable stars (Loeb et al., 2014; Maoz et al., 2015).

- *Magnetar flares:* Within one month of publication of the Lorimer event, Popov & Postnov (2007) had proposed that hyper-flares from cosmological magnetars could give rise to highly energetic millisecond bursts. They suggested that an extragalactic soft gamma-ray repeater (SGR) could be generated in a magnetar magnetosphere due to "tearing mode" instability. The emission mechanism of these "millisecond Extragalactic radio burst (mERBS)", as they were - and might have ultimately been - called, was described in 2002 by Lyutikov (2002). The model requires a cosmological population to achieve the large DMs and event rates.

- *Supernova remnant pulsars:* In this model FRBs are very young pulsars, in external but non-cosmological galaxies. Their large dispersion measure from free electrons in their supernova remants, which also Faraday rotates and scatters the burst. The dispersion measure is given by,

$$\mathrm{DM} \approx \frac{\mathrm{x}_e \mathrm{M}_{\mathrm{ej}}}{m_p \frac{4\pi}{3} v_{\mathrm{ej}}^2 t^2} \tag{1.13}$$

, where x_e, M_{ej} are the free electron fraction and supernova ejecta mass respectively, v_{ej}, is the ejecta velocity, and t is the age. Proposed by Connor et al. (2016c) as a way of explaining all the observed phenomenology locally, it has been further studied by Piro (2016) and Lyutikov et al. (2016). One firm prediction of this model is that the flux distribution of FRBs will be strictly Euclidean, since their progenitors are in the local Universe ($z \lesssim 0.1$). Further observational consequences of this model, including repetition, are described in **??**.

- *Circum-nuclear magnetars:* This model (Pen & Connor, 2015) infers the existence of radio-loud magnetars at the centers of galaxies from the high-DM (1778 pc cm^{-3}), high-RM (-6.4×10^4 rad m^{-2}) SGR J1745-2900, which is < 1 pc from Sgr A*. Galactic centers would therefore provide the dispersive electron plasma and the bursts would not need to be at cosmological distances, similar to the supernova remnant model. The source of the pulse would be a radio-flare from the nuclear magnetar, similar to the mechanism in (Popov & Postnov, 2007). One issue with this model is the dearth of low-DM FRBs; since radio-loud magnetars exist outside of galactic centers, the model demands that the nuclear sources preferentially emit radio flares.

- *Super-giant pulses:* This is a class of models in which FRBs are akin to giant pulses from the Crab, but several orders of magnitude more energetic. The Crab pulsar, which exhibits the highest known brightness temperatures in the Universe, can get up to ∼MJy. Cordes & Wasserman (2016) provided a detailed investigation into the physical limitations of coherent emission around 1 GHz. Connor et al. (2016c) also use super-giant pulses as the source of the radio bursts. In that model, giant pulses are necessarily brighter earlier in the young pulsar's life ($\lesssim$ 500 years), which explains why we do not see Crab giant pulses as energetic as an extragalactic FRB. Any version of this model would expect repetition.

1.3.2 Empirical constraints

As of early 2014 no FRB observation presented any standout clues about the emission mechanism. They were all observed only in Stokes I and none had been seen to repeat. With FRB 140514, the first real-time detection, full Stokes information was recorded and immediate follow up observations were carried out in other wavelengths (Petroff et al., 2015b). It was found to have 21$\pm$7% circular polarization and negligible linear polarization. No counterpart was found after 12 telescopes from radio to X-ray monitored the FRB field in the days following, ruling out local ($z < 0.3$) SNe and long GRBs (Petroff et al., 2015b).

Between late 2015 and early 2016, there was a rapid succession of significant observational claims. FRB 110523, was the first, published in fall of 2015 (Masui et al., 2015). It was the only burst after FRB 140514 for which polarimetry could be done. It was found with the GBT IM data in archival data, and had 44$\pm$3% linear polarization (Masui et al., 2015). Interestingly, the source was Faraday rotated with an RM of -186 rad m^{-2}, which is roughly two orders of magnitude greater than what would be expected in the IGM (Oppermann et al., 2015). This seemed to put strain on the cosmological interpretation of FRB 110523, since the dispersion (caused by free electrons) and the Faraday rotation (caused by free electrons + a magnetic field), would be coming from two different places.

Another exceptional feature of this event was the evidence for two separate scattering screens. Scintillation was found with a $\sim$MHz decorrelation length as well as temporal broadening at millisecond timescales. The μs scintillation is expected arise when the source enters our Galaxy, implying the ms scattering must happen somewhere local to the source (Masui et al., 2015). The FRB also showed a polarization angle swing, similar

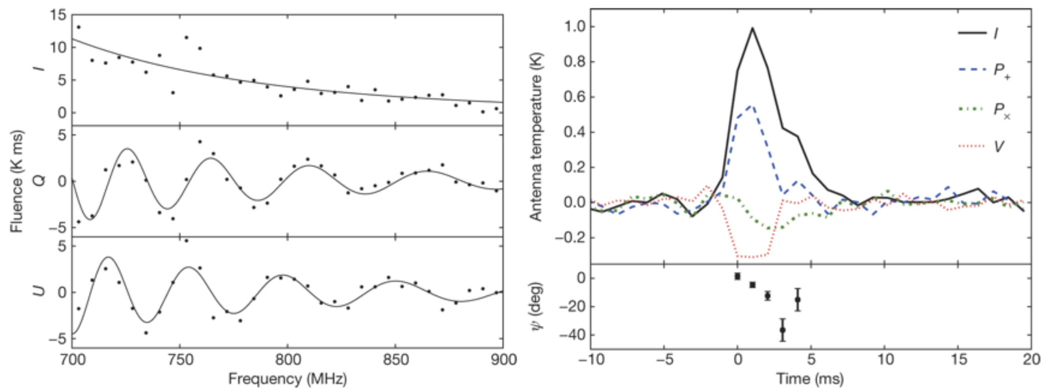

Figure 1.2: Figure adapted from Masui et al. (2015) of FRB 110523. The left panel shows the large Faraday rotation and the right panel shows the dedispersed, frequency-averaged pulse profiles for total intensity, Stokes V, and the two linear polarizations. One can also see the polarization angle swing across the burst.

to that seen in pulsars, indicative of a rotating object. These facts, along with constraints on the dispersing electron's plasma frequencies, ruled out Galactic models. They also lent credence to rotating neutron star models, whether magnetar flares or supergiant pulses from young pulsars.

Another major claim was made by Keane et al. (2016), who found a host galaxy at $z = .492$ that appeared to be associated with an FRB. The localization was not based on a VLBI observation, but rather a coincident radio "afterglow" in the same ∼13" Parkes field. Part of a multi-wavelength follow up, the Australia Telescope Compact Array (ATCA), observing at 5.5 and 7.5 GHz, found a radio source whose flux seemed to fall off a factor of a few in roughly 6 days. The authors interpreted this as a fading transient, not unlike radio afterglows of short GRBs, favouring the compact object merger scenario. However, the validity of this galaxy's association with the FRB has been called into question. Shortly after the press release of (Keane et al., 2016), Williams & Berger (2016) did a further observation suggesting the source was in fact a *variable* rather than a transient, the latter of which are quite rare.

By far the most important new observation in the field is the discovery of FRB 121102's repetition (Spitler et al., 2016). 121102 was found to repeat 10 times in (Spitler et al., 2016) and 6 additional times in (Scholz et al., 2016). With one fell swoop the numerous models in the cataclysmic class were falsified. The exception being if there are two or more populations of FRBs with disparate progenitors, in which case "Type A FRBs", for instance, are known to be non-destructive. The sub-bursts were all also detected with Arecibo, many of them getting down to the telescope's fluence limit, implying most of its bursts were undetectable (Spitler et al., 2016; Scholz et al., 2016). Its DM changed by less than measurement uncertainty of ~ 6 pc cm^{-3} over the course of several years, though the spectral properties varied wildly from burst to burst. Finally, its repetition was highly non-Poissonian, with 6 of the first 10 appearing in single twenty minute pointing, despite monitoring the field for over ten hours. Such non-Poissonian behaviour was predicted in (Connor et al., 2016b) and has consequences for survey strategy.

1.4 Pulsar thing

1.5 Thesis Outline

In Chapter **??** we introduce the Canadian Hydrogen Intensity Mapping Experiment (CHIME). We first describe the science goals of the three projects. The instrument is discussed, including a step-by-step outline of the signal chain. This chapter's purpose is to provide context for the other chapters, which either involve CHIME directly or are relevant to its science. Also presented is early analysis work that I have done, including the discovery of various unexpected beam properties of the CHIME Pathfinder. Most of the work in this chapter was done by the collaboration as a whole. For example, the F-engine was built by Kevin Bandura, Jean Francois Trempe, and Matt Dobbs, but it still seemed necessary to describe that step in the data processing. Details about the instrument in this chapter overlap with the work published in (Bandura, 2014), (Newburgh et al., 2014), and (Berger et al., 2016), all of which I co-authored.

In Chapter **??** we delineate the commissioning of CHIME Pathfinder's beamformer, prefaced by a mathematical introduction to digital beamforming. The work described was done largely by myself, but with the aid of several key people. Andre Recnik was instrumental in networking and miscellaneous computing issues related to the back-end. My supervisor, Keith Vanderlinde was also critical in guiding this project in the right direction. The real-time FRB VLBI survey, starting with the burst-search that was attached to the Pathfinder's formed-beam, relied on the direction of Ue-Li Pen and the programming expertize of Kendrick Smith and Kiyo Masui.

Chapter **??** presents a theory for the origin of FRBs in which the bursts are extragalactic but non-cosmological pulsars in the remnants of recent supernovae. We published this model in Monthly Notices of the Royal Astronomical Society (MNRAS) at a time when FRBs were not known to repeat and most authors assumed they were cosmological and cataclysmic (Connor et al., 2016c). This work was done in collaboration with Ue-Li Pen and Jonathan Sievers. It was Jonathan Sievers' idea to place FRBs in young, compact SNe remnants. I then built a model to represent that environment, infer its consequence, and feasibility in terms of event rate and energetics. With Ue-Li I also worked on the observables of the supernova remnant hypothesis as well as other models. These are included in table **??**.

Chapter **??** is called "FRB Statistics". In it we analyze a number of statistical problems that have come up since the discovery of FRBs. These include their purportedly non-uniform latitudinal distribution and constraints on their repeat rate. These sections were adapted from a paper published in MNRAS in collaboration with Ue-Li Pen and Niels Oppermann (Connor et al., 2016b). My contribution to this paper included building a model for FRB repetition based on $1/f$ noise and doing mock-follow-up Monte Carlo simulations. Working with Ue-Li, I also developed a test for the latitudinal dependence of the burst-rate that is based on a biased coin flip. This chapter later investigates the all-sky event rate below L-band, and forecasts for CHIME FRB and several other low-frequency experiments. The corresponding sections were derived from (Connor et al., 2016a), again published in MNRAS. As lead author I carried out most of the calculations, excluding the frequentist/baysian estimates for event rate, which were conceived of by Niels Oppermann. Hsiu-Hsien Lin and Kiyo Masui, who are members of the GBT IM experiment, provided details about the survey and its dataset. Ue-Li Pen was crucial in the overall direction of the research, particularly in focusing on easily calculable statistics and the idea to forecast by comparing similar surveys. The final paper whose work ended up in Chapter **??** was (Oppermann et al., 2016), accepted to MNRAS. This work was regarding the signal-to-noise distribution of FRBs and the use of a $V/V_{\rm max}$ test. Niels Oppermann created the plots and wrote code to calculate the α/event-rate posterior, but most of the theoretical work was done in meetings with Ue-Li Pen, myself, and Niels.

The final chapter investigates the sub-millisecond structure of individual pulses from B0329+54. The "microstructure" is studied in full polarization, and its quasi-periodicities are found to be common within a pulse for all Stokes parameters, but not common between pulses. This work was done with the supervision of Ue-Li Pen, who provided physical insight and guidance on the project's direction.

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