Long Wavelength Astrophysics

by

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Abstract

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Acknowledgements

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Introduction

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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 ~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).

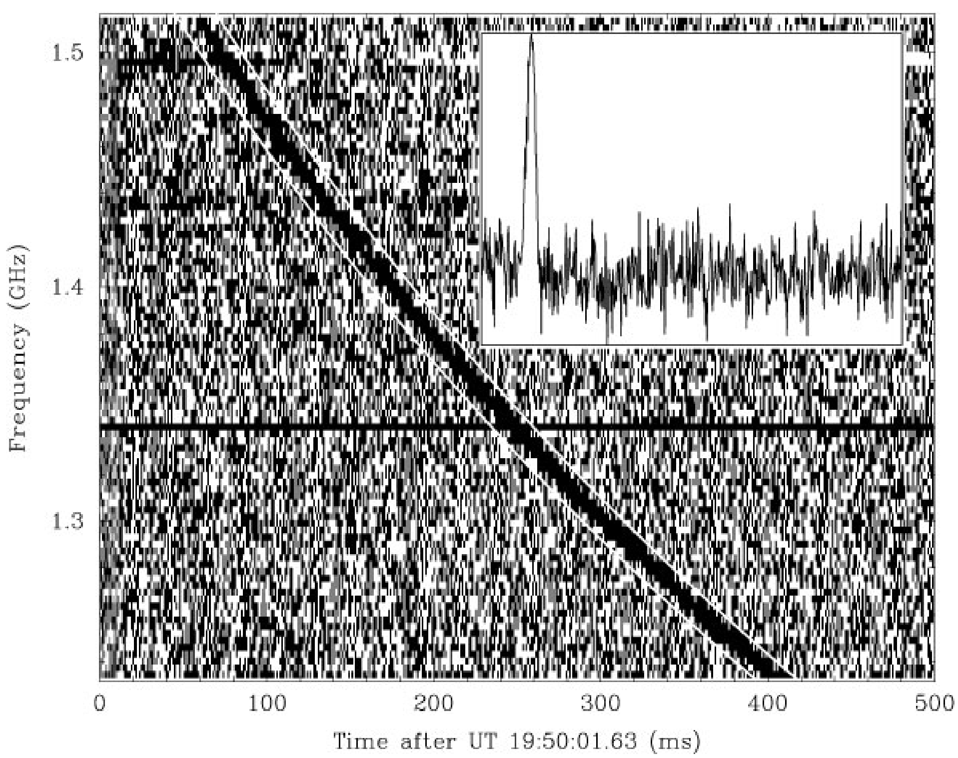

Figure 1.1: Figure reproduced from (Lorimer et al., 2007) of the so-called Lorimer Burst, which is the first known FRB.

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 (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. (2015c) 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., 2015c). 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

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

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 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 and interpretation

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., 2015b), 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,

$$\lambda_{obs} \propto (1+z)\left(\sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_\mathrm{M}}\right)^{0.5}(1+\mathrm{z})^{-3/2}\right]\right)^{1/4}, \tag{1.1}$$

  gives observable wavelengths of $\sim$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,

$$\mathrm{DM} \approx \frac{\mathrm{x}_e \mathrm{M}_{\mathrm{ej}}}{m_p \frac{4\pi}{3} v_{\mathrm{ej}}^2 t^2} \tag{1.2}$$

  , 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. (2016b) 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 $\sim$MJy. Cordes & Wasserman (2016) provided a detailed investigation into the physical limitations of coherent emission around 1 GHz. Connor et al. (2016b) 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.

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 (**?**). 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 same field.

FRB 110523 was the next burst for which polarimetry could be done. It was found with the GBT IM data in archival data, and had 44$\pm$3% linear polarization. Interestingly, the source was Faraday rotated

1.4 Pulsar thing

1.5 Thesis Outline

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