Fast Radio Bursts

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1 Introduction

1.1 History of FRB's

At the end of their lifetime, stars like our sun run out of nuclear fuel and the fusion process that powers them stops. Stars ≈ 10 times the mass of our sun or larger can then explode into a supernova, sometimes collapsing into a neutron star. Neutron stars get their name from their immense gravitational force, which causes electrons and protons within them to join, forming neutrons. For smaller stars, there is not enough gravitational force for this process to occur, and the cores collapse into a white dwarf instead. These star remnants are magnetised and rotate rapidly, causing them to emit radio waves at precise regular intervals. In 1968, these radio waves were measured for the first time and given the name pulsars, after the repeating pulse of radio waves they emit. There have since been many radio telescope surveys of pulsars.(*Encyclopædia Britannica* n.d.)

In 2007, a strange signal was detected in a archival survey of pulsar data gather by Australia's Parkes Observatory. Lorimer et al. 2007 This signal was 30-Jy, lasted less than 5e-3 seconds, and roughly 1GPs away from earth. Lorimer et al searched through large amounts of pulsar data to find this signal by using a matched filtering technique to detect pulses of duration 1ms-1s with a signal to noise ratio of greater than four. This signal had a frequency delay - different frequencies of the burst arrived at slightly different times. This is because the clouds of ionized plasma that sit between galaxies have a frequency dependant refractive index, so the frequency components of light travel at different speeds in it. This frequency dispersion is more pronounced as the distance from the source increases. This delay is known as a dispersion measure or DM. Looking at the spectrum for the detected FRB in the Lorimer survey, we see the characteristic frequency dependant delay. Since the discovery of these fast radio bursts in 2007, there have been several more measurements of these phenomena, some of which are even regularly repeating, but there is still no consensus on what could be causing them. (*Encyclopædia Britannica* n.d.)

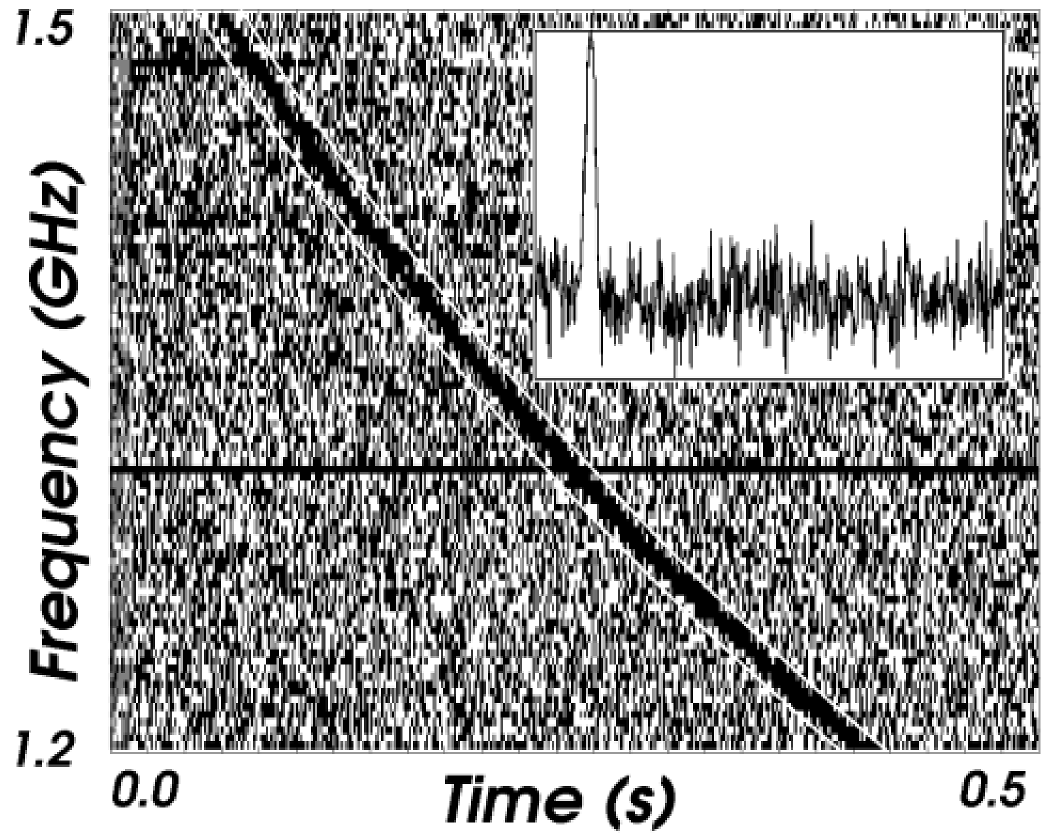

Figure 1: The frequency spectrum of the very first FRB discovered. From the Lorimer paper: *"The dispersion is clearly seen as a quadratic sweep across the frequency band, with broadening towards lower frequencies.... The horizontal line at 1.34 GHz is an artifact in the data caused by a malfunctioning frequency channel."* (Lorimer et al. 2007)

1.2 What is an FRB?

As described in (Petroff, Hessels, and Lorimer 2019), Fast radio bursts are defined as short radio wave emissions that last 1e-3 seconds or less. Current measurements put the frequency range of these at between 400 MHz and 8 GHz. At their source, the FRB's are very intense and energetic, but in travelling to earth through the intergalactic medium, they dissipate until they are very weak, with the aforementioned "Lorimer burst" measured at 30 Jy. Fast radio bursts are unresolved, appearing to be emitted from point sources. As described above, the radio bursts have a frequency dispersion. The time difference in arrival between the highest and lowest frequency components can be quantified in milliseconds as such:

$$\Delta t \approx 4.15(\nu_L^{-2} - \nu_H^{-2})DM \tag{1}$$

Here ν_L is the lowest frequency component of the signal, ν_H is the highest frequency component of the signal, and DM is the dispersion measure of the interstellar medium, which depends on the density of the electrons in the plasma along the path of the radio burst between the source and the earth.

$$DM = \int_0^d n_e(l)dl \tag{2}$$

Here d is the distance between the earth and the radio burst source, and n_e is the electron number density in the plasma.

1.3 The Significance of FRB's

First and foremost, FRB's are significant because of the mystery they present: it would be interesting to know what in the universe could create such a strong burst of energy in such a small amount of time. There is currently no consensus on what creates these fast radio bursts, and resolving their origin would not only be a very compelling puzzle to solve, but would also probably result in the discovery of a new class of astrophysical event.

Aside from being an interesting problem, FRB's also have potential application in cosmology. Because the time difference in arrival between the highest and lowest frequency components of the signal can be described by equation (1) as above, we can then solve for the DM of the interstellar medium, and infer properties of it from this. This is something that FRB's are uniquely positioned to do: because other cosmological radio sources such as gamma ray bursts and radio quasars lack the sharpness of the FRB, it is difficult to use them to measure the intergalactic medium. (Zheng et al. 2014) This was put nicely by (Zheng et al. 2014), who in their paper on this topic stated that *"The pulse nature, the high rate, and the extra-galactic origin make* *the Sparker-like events and FRBs well suited for being used as a potentially powerful probe to the inter-galactic medium."*

Some of the applications of FRB's so far include combining the dispersion measure (DM) observation with the Faraday rotation of the signal to measure the mean magnetic field between the source of the FRB and its origin, which can *"inform models of galaxy formation and cosmology"* (Ravi et al. 2016). Another use of FRB's was to combine the dispersion measure (DM) observation with the red-shift of the signal to derive the density of ionized baryons in the intergalactic medium between the source and earth. (Keane et al. 2016)

2 The Matched Filter

Matched filtering is a signal processing technique in which one correlates a known signal with a noisy, unknown one to see if the known signal appears in the unknown signal. In the jargon of LTI systems theory, when one knows the pattern one wants to detect in a noisy signal, the matched filter h is defined as being the linear filter that returns a signal with the highest possible signal to noise ratio (SNR) when convolved with the noisy signal. Because matched filtering is just correlating a known template signal with an unknown noisy signal, this means that the matched filter "h" is just the conjugated time reversed version of the original template signal.

$$C = \int_{-\infty}^{\infty} f(t+\tau)g(\tau)d\tau \tag{3}$$

This is the mathematical definition of the matched filter. Here f is the template signal one wants to detect, and g is the noisy signal. C is then the resultant correlation that tells one if f is part of g.

3 FRB Detection

3.1 Hardware

Researchers use two types of radio telescopes to detect FRBs, single dish and interferometric radio telescopes. Single dish radio telescopes have the advantage of large dish size and thus sensitivity to signals, but have trouble attributing FRBs to specific locations due to having only one receiver. In contrast to the single large dish approach, interferometric radio telescopes have several smaller dishes, and use aperture synthesis techniques to combine their signals. Interferometeric telescopes are good at determining the location of sources, and are easier to adjust than single dish telescopes. The downside of interferometric RT's is that combining data streams from their many apertures is computationally expensive. Also, interferometric telescopes are less flexible with what frequency bands they can observe. (Petroff, Hessels, and Lorimer 2019)

3.2 Detection Process

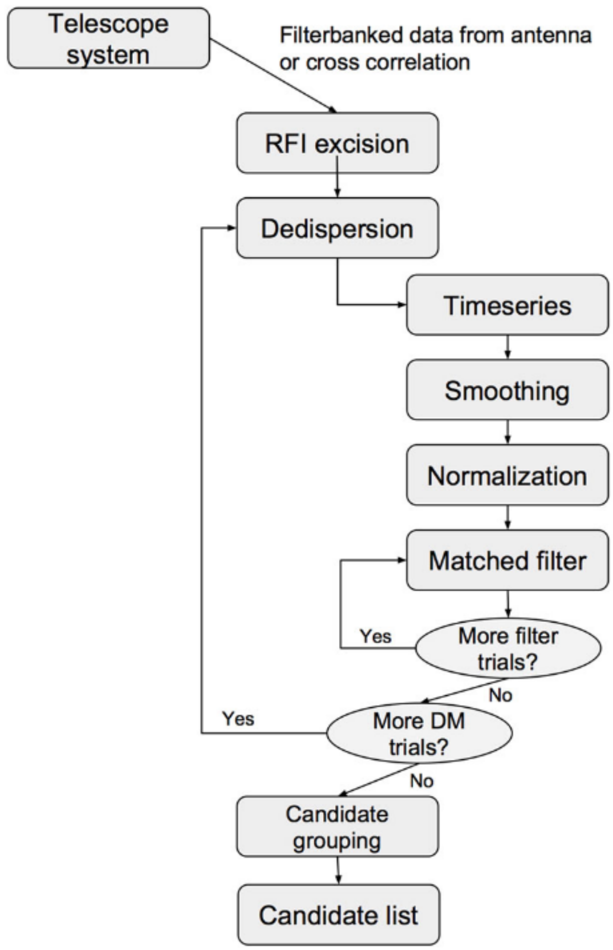

Figure 2: This is a diagram outlining the standard way to detect FRB's. Firstly, the radio telescope receives the electromagnetic signal of the FRB, which is stored on a computer. This data is then cleaned of radio frequency interference (RFI) by time frequency masking. The next step is De-dispersion. This step corrects the (unknown) DM in the data by searching a large trial space for candidate DM's. A time series is then extracted from this de-dispersed data, which can be searched for any pulses. Once these pulses are found, they are normalized, and amongst the set of pulses, FRB candidates are found by using matched filtering, convolving the time series with boxcar functions of the expected width of the pulse, which then gives us our FRBs. Diagram and process description taken from (Petroff, Hessels, and Lorimer 2019)

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