



UNIVERSITY OF CAPE TOWN

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ASTRONOMY

Searching for an optical counterpart to Fast Radio Bursts

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Contents

1	Introduction	4
1.1	Discovery of Fast Radio Bursts	4
1.2	Propagation effects	4
1.2.1	Dispersion	4
1.2.2	Scattering and scintillation	5
1.2.3	Faraday rotation	6
1.3	Repeating and non-repeating Fast Radio Bursts	7
1.4	Properties of Fast Radio Bursts	8
1.4.1	Energy and event rates	8
1.4.2	Spectral and temporal properties	8
1.4.3	Polarisation properties	9
1.5	Current FRB population	10
1.6	Progenitor models	10
1.6.1	Isolated neutron star models	11
1.6.2	Interacting compact object models	12
1.6.3	Cataclysmic models	13
1.6.4	Exotic models	13
1.7	Emission mechanisms	14
1.7.1	Models invoking compact object magnetospheres	14
1.7.2	Models invoking the synchrotron maser mechanism	14
1.8	Justification for an optical counterpart search	16
1.9	Previous searches for counterparts	17
2	Instruments	20
2.1	MeerKAT and MeerTRAP	20
2.2	MeerLICHT	22
2.3	Overview of attempts to simultaneously observe FRBs using MeerLICHT and MeerKAT	23
3	Contemporaneous optical-radio observations of a fast radio burst in a close galaxy pair	25
3.1	Introduction	26
3.2	Radio Observations and data reduction	27
3.2.1	MeerTRAP pipeline and FRB 20230808F detection	27
3.2.2	Localisation	28
3.2.3	Burst structure and timing analysis	29
3.2.4	Polarisation and rotation measure	31
3.3	Host galaxy and optical counterpart search	33

3.3.1	Identification of host galaxy	33
3.3.2	MeerLICHT optical counterpart search	33
3.3.3	SALT spectra	35
3.4	FRB 20230808F characteristics	36
3.4.1	Radio flux and fluence	36
3.4.2	Host galaxy contribution to propagation properties	37
3.4.3	Optical flux limits	38
3.4.4	Fluence ratio limit and optical luminosity limit	38
3.5	FRB 20230808F in context	40
3.5.1	Comparison to previous optical limits	40
3.5.2	Constraints on the synchrotron maser model	46
3.5.3	Host galaxy and redshift	46
3.6	Summary and conclusions	47
4	FRB 20240619D - the first repeater discovered by MeerTRAP	50
4.1	Discovery of FRB 20240619D	50
4.2	MeerKAT observations	50
4.3	MeerLICHT observations	51
4.4	Analysis of MeerLICHT data	51
4.5	Comparison to previous optical limits	55
4.6	Conclusions and future analysis	63
5	Conclusions and recommendations for future work	65

Statement on verbatim inclusion of first-author paper in this thesis

I confirm that I have been granted permission to include the following publication(s) in my Master's dissertation, and where co-authorships are involved, my co-authors have agreed that I may include the publication(s):

- “*Contemporaneous optical-radio observations of a fast radio burst in a close galaxy pair*”, submitted to the Monthly Notices of the Royal Astronomical Society, and presented verbatim in this thesis as Chapter 3.

Chapter 1

Introduction

1.1 Discovery of Fast Radio Bursts

Fast Radio Bursts (FRBs) are bright, milli-second duration pulses of radio emission that are of extragalactic origin. The first FRB was discovered in 2007 in archival pulsar data taken in 2001 with Murriyang, the Parkes 64m radio telescope (Lorimer et al., 2007). It had a dispersion measure (DM, Section 1.2.1) which showed that it originated from far beyond the Milky Way, and thus that it had a very high luminosity. For several years, only this single FRB, the “Lorimer burst”, was known, causing its astronomical nature to be questioned. This was not helped by the detection of “peryttons”, which were transients of terrestrial origins that displayed similar dispersion-like properties to FRBs and which were also only being detected by Parkes. They were typically detected in all 13 Parkes beams, suggesting that they were not located in the far-field, as opposed to the “Lorimer burst”. Perytons were later found to be the result of a microwave door at the Parkes site being opened prematurely (Petroff et al., 2015b). Finally, in 2013, four additional FRBs were reported by Thornton et al. (2013), providing evidence that FRBs were indeed genuine extragalactic astrophysical phenomena.

1.2 Propagation effects

1.2.1 Dispersion

When signals from FRBs travel towards us, they pass through the ionised component of the interstellar medium (ISM), and we observe an effect called dispersion, where light is delayed as it passes through ionised plasma, which has a refractive index that depends on frequency. The velocity of light changes with angular plasma frequency ω_p as follows:

$$v_g = c\sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}, \quad (1.1)$$

where v_g is the group velocity of the propagating electromagnetic waves and ω is the angular frequency of the signal, which is related to the linear frequency ν as follows:

$$\omega = 2\pi\nu = 2\pi\left(\frac{c}{\lambda}\right), \quad (1.2)$$

where c is the speed of light and λ is the wavelength¹. As is clear from Eq. 1.1, longer wavelengths of light experience a larger delay when passing through ionised plasma. Additionally, the delay is proportional to the amount of ionised ISM through which the waves propagate, given that:

$$\omega_p = \sqrt{\frac{e^2 n_e}{\pi m_e}}. \quad (1.3)$$

The dispersion measure (DM) describes the degree to which signals are delayed, and corresponds to the column density of free electrons along the line of sight between the observer and the source. It is therefore frequently used as a proxy for distance, and is given as follows:

$$\text{DM} = \int_0^d n_e(l) dl, \quad (1.4)$$

where d is the path length and $n_e(l)$ is the electron number density along the path. The units of DM are pc cm^{-3} . The time delay between two frequencies ν_1 and ν_2 due to dispersion is given by:

$$\Delta t = D \times \text{DM} \times (\nu_1^{-2} - \nu_2^{-2}), \quad (1.5)$$

where D is the dispersion constant, defined as:

$$D \equiv \frac{e}{2\pi m_e c}. \quad (1.6)$$

The total DM for a FRB is given by the sum of various components that contribute to it, as follows:

$$\text{DM}_{\text{FRB}} = \text{DM}_{\text{MW}} + \text{DM}_{\text{halo}} + \text{DM}_{\text{IGM}} + \frac{\text{DM}_{\text{host}}}{1+z}, \quad (1.7)$$

where DM_{MW} is the contribution to the total DM from the Milky Way (MW) ISM, DM_{halo} is the contribution due to the MW halo, DM_{IGM} is the DM contribution from the intergalactic medium (IGM), DM_{host} is the contribution from the FRB host galaxy, and z is the redshift. The circumgalactic media of intervening galaxies and the FRB's local environment can also contribute to dispersion. The DM_{host} is scaled by a factor of $(1+z)^{-1}$ to account for cosmological time dilation. The contribution to the DM from the IGM is also dependent on redshift, and the relationship is approximately linear at low redshifts (Ioka, 2003; Inoue, 2004). The contribution from the MW halo is approximately $30 - 200 \text{ pc cm}^{-3}$ (Prochaska & Zheng, 2019; Yamasaki & Totani, 2020), and DM_{MW} is approximated using the NE2001 (Cordes & Wasserman, 2016) and YMW16 (Yao et al., 2017) electron density models. An example of pulse dispersion can be seen in Figure 1.1, taken from Lorimer & Kramer (2004).

1.2.2 Scattering and scintillation

Electromagnetic waves propagating through the ionised ISM are scattered in different directions, with the amount of scattering depending on their frequency. They experience a varying refractive index due to the changes in the electron density in the ISM, causing slight bending of their wavefronts. This means that, for a signal made up of different wavelengths, even if all of the light was emitted simultaneously, the different wavelengths will travel along different paths to reach us, and as such will arrive at different times. This causes the convolution of the intrinsically sharp pulse with a one-sided decaying exponential, which has a time constant

¹ $\nu = c/\lambda$ is the case for a wave in a vacuum. For a wave traveling through ionised plasma, the relationship is $\nu = v_p/\lambda$, where v_p is the phase velocity, which depends on the refractive index of the medium.

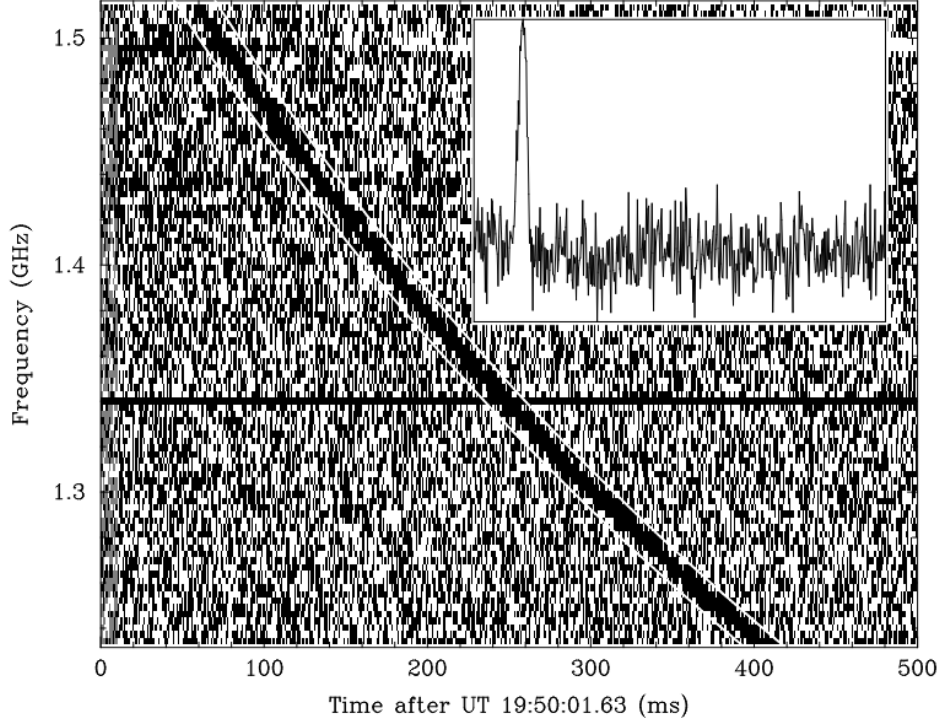


Figure 1.1: Effects of dispersion are visible in the Parkes observation of the “Lorimer burst”, with lower frequency components of the pulse arriving later than higher frequency components. Figure from Lorimer et al. (2007).

called the scattering timescale, τ_s . Assuming the simplest possible scenario, where all scattering originates from a thin screen located at the midpoint of the propagation path, the scattering timescale depends on frequency as follows (Lorimer & Kramer, 2004):

$$\tau_s \propto \nu^{-4}, \quad (1.8)$$

meaning that longer wavelengths of light are much more scattered than shorter wavelengths.

The inhomogeneous and turbulent conditions of the ISM cause different components of an FRB signal to interfere both constructively and destructively with one another as the signal reaches the observer. This results in the observer seeing a pattern of intensity variations that depends on frequency and timescale. This phenomenon is known as scintillation. The scintillation bandwidth, $\Delta\nu$, is inversely proportional to the scattering timescale as follows (Lorimer & Kramer, 2004):

$$\Delta\nu \propto \tau_s^{-1}. \quad (1.9)$$

1.2.3 Faraday rotation

Electromagnetic waves can be characterised by the Stokes parameters I , Q , U , and V . Stokes I represents the total intensity of a polarised electromagnetic wave, and can be further decomposed as follows into the remaining Stokes parameters:

$$I \geq \sqrt{Q^2 + U^2 + V^2}, \quad (1.10)$$

where Q and U represent the linear polarisation, given by $L = \sqrt{Q^2 + U^2}$, and V is the circular polarisation. The linear polarisation angle (PPA, introduced in Section 1.4.3) of a polarised signal changes with wavelength as:

$$\text{PPA} \propto \text{RM}\lambda^2, \quad (1.11)$$

where RM is the Faraday rotation measure and λ is the wavelength. Faraday rotation is a propagation effect where the plane of polarisation of linearly polarised light rotates as it passes through a magnetised medium, with a positive RM indicating a magnetic field directed towards the observer. The RM is given by:

$$\text{RM} = -0.81 \int_0^d B(l)_{\parallel} n_e(l) dl, \quad (1.12)$$

where $B(l)_{\parallel}$ is the magnetic field parallel to the line of sight in μG and n_e is the electron density in cm^{-3} .

When the RM of a FRB is thought to primarily originate from its host galaxy and local environment, and therefore from cosmological distances, then the RM contribution from the host must be redshift-corrected as follows:

$$\text{RM}_{\text{host}} = \text{RM}_{\text{obs}}(1+z)^2. \quad (1.13)$$

The contribution to the RM from the IGM is thought to be generally small (Ravi et al., 2016), while the MW contribution can be estimated using the Faraday sky model from Hutschenreuter et al. (2022). FRB RMs can be determined using the RM synthesis technique, which involves identifying the maximum of the Fourier transform of the linearly polarised signal (Burn, 1966; Brentjens & de Bruyn, 2005). Stokes QU-fitting can also be used to measure RM (e.g. O’Sullivan et al. 2012).

1.3 Repeating and non-repeating Fast Radio Bursts

For almost a decade, all FRBs discovered were only observed to burst once. This changed in 2016, when the first repeating FRB was reported by Spitler et al. (2016). FRBs are now sub-divided into two main groups: repeating and non-repeating FRBs. Most of the more than 700² FRBs discovered at the time of writing fall into the non-repeating class, meaning that they have only been observed once. On the other hand, there are ~ 60 published FRBs which have been observed multiple times, and which thus fall into the repeating class (CHIME/FRB Collaboration et al., 2023). However, repeating FRBs have generally been published faster than non-repeating FRBs, and there are as yet unpublished FRB catalogs; the true observed fraction of repeating FRBs is only around 3 per cent (CHIME/FRB Collaboration et al., 2023).

Repeating FRBs do not display periodic bursts, meaning that there is no underlying period detected in the arrival times of the bursts; rather, at least some go through “activity cycles”, which refers to periods of time during which these FRBs display elevated burst rates. Although the bursts during these activity cycles are not themselves periodic, FRB 20180916B (Amiri et al., 2020) is known to exhibit periodic activity cycles, and FRB 20121102A (Cruces et al., 2020; Rajwade et al., 2020) is thought to as well (Li et al., 2024).

The question of whether repeating and non-repeating FRBs have the same underlying mechanisms has not been answered yet, but the two classes do appear to have differences in their burst structures: many repeating FRBs have multiple burst components, which display a downward drift in frequency (Hessels et al., 2019; CHIME/FRB Collaboration et al., 2019; Fonseca et al., 2020; Day et al., 2020). This is known as the “sad trombone effect”. Non-repeating FRBs can either have a burst with a single component that can be either broad or narrowband, or they can have multiple components that all peak at the same frequency. Repeating FRBs, on

²<https://www.wis-tns.org/>

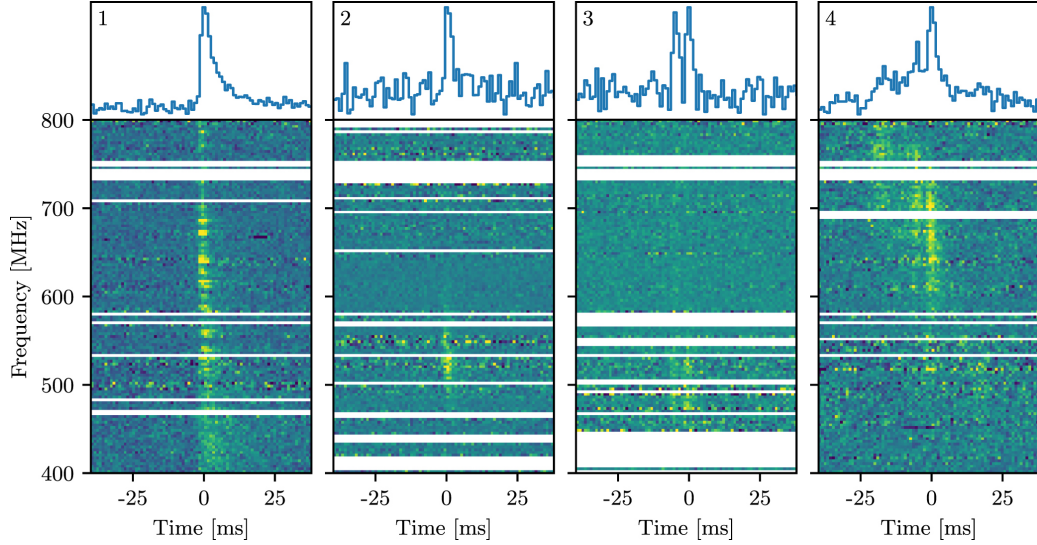


Figure 1.2: Shown above are the four different FRB morphologies described by Pleunis et al. (2021). From left to right, they are: a broadband single-component FRB, a narrowband single-component FRB, a FRB with multiple components peaking at the same frequency, and lastly a FRB displaying the “sad trombone effect”, with downward drifting burst components. Figure taken from Pleunis et al. (2021).

the other hand, tend to be narrower in frequency, as well as wider in time, than non-repeaters (Pleunis et al., 2021). Examples of these different FRB morphologies are shown in Figure 1.2 taken from Pleunis et al. (2021).

1.4 Properties of Fast Radio Bursts

1.4.1 Energy and event rates

FRBs are highly energetic, with typical peak flux densities between $0.1 - 100$ Jy, which is similar to those of pulses from pulsars (Petroff et al., 2019). This is at least partly due to the fact that both pulsars and FRBs are observed using the same telescopes, which have specific sensitivities. Their isotropic energies range from $\sim 10^{35} - 10^{43}$ erg, and their isotropic peak luminosities range from $\sim 10^{38} - 10^{46}$ erg s $^{-1}$ (Ravi et al., 2019; Bochenek et al., 2020), making them $\sim 10^{12}$ times more luminous than pulsars (Nimmo et al., 2022).

The celestial distribution of FRBs discovered to date appears to be isotropic, and the all-sky rate, measured in FRB sky $^{-1}$ day $^{-1}$, is given for a specific fluence threshold. Most of the estimates lie in the range of $\sim 10^3 - 10^4$ sky $^{-1}$ day $^{-1}$ above a fluence threshold of 1 Jy ms (e.g. Champion et al. 2016; Shannon et al. 2018; Bhandari et al. 2018; Farah et al. 2019; CHIME/FRB Collaboration et al. 2021; Jankowski et al. 2023; Pastor-Marazuela et al. 2024).

1.4.2 Spectral and temporal properties

FRBs are detected across a range of wavelengths, from 110 MHz (FRB 20180916B; Pastor-Marazuela et al. 2021; Pleunis et al. 2021) up to 8 GHz (FRB 20121102A; Gajjar et al. 2018). It is worth noting, however, that there are many FRBs which are observed to emit across the entire available bandwidth of the instruments with which they are detected, meaning that our understanding of their frequency ranges could be limited by the instruments available to us. Repeating FRBs, however, tend to be narrowband, as mentioned in Section 1.3 (Zhou et al., 2022; Pastor-Marazuela et al., 2021; Pleunis et al., 2021). Higher frequencies are less

affected by dispersion, meaning that it becomes more challenging to differentiate between radio frequency interference and true FRB signals. This could be partly responsible for the lack of FRBs detected at high frequencies (Zhang, 2023). Another contributing factor could be lower sensitivity at higher frequencies (Law et al., 2017), along with the current lack of wide-field, high-frequency (>3 GHz) FRB searches.

The temporal width W of a FRB, representing its observed duration, is typically on the order of milliseconds (although shorter-duration FRBs are more challenging to detect due to observational bias, and bursts as short as a few microseconds have been detected; Snelders et al. 2023). However, for both non-repeating and repeating FRBs with multiple components, the width of each component is usually on the same order as that of a single-component FRB, meaning that the total duration of these multi-component bursts can be tens of milliseconds, or, in the case of FRB 20191221A, even up to 3 seconds (CHIME/FRB Collaboration et al., 2022). The width of an FRB is a combination of the intrinsic burst duration, broadening due to scattering that occurs as the FRB propagates towards the observer, and broadening due to instrumental effects. The *sad trombone* effect introduced in Section 1.3 is also a temporal property. Pleunis et al. (2021) performed a study on a large sample of FRBs, and categorised bursts into four main morphologies: these are “simple broadband”, “simple narrowband”, “temporally complex” and “downward drifting”. As discussed in Section 1.3, non-repeaters can fall into the first three morphologies, while many repeaters fall into the “downward drifting” category (see Figure 1.2).

1.4.3 Polarisation properties

FRBs have generally been observed to exhibit strongly polarised emission, with most FRBs exhibiting linear polarisation fractions exceeding 30 per cent, and with most repeating FRBs displaying 100 per cent linear polarisation (e.g. Michilli et al. 2018; Fonseca et al. 2020; Day et al. 2020; Kumar et al. 2020; Niu et al. 2022; Bhardwaj et al. 2021). Non-repeating FRBs generally appear to have lower levels of linear polarisation than repeaters, although Pandhi et al. (2024) found no statistically significant difference between the linear polarisation fractions of repeaters and non-repeaters. On the other hand, circular polarisation is a lot less common in general; very few repeating FRBs display circular polarisation, although there are exceptions (e.g. Kumar et al. 2022; Xu et al. 2022), and there are only a few non-repeating FRBs that display significant amounts of circular polarisation (Caleb et al., 2018; Masui et al., 2015; Petroff et al., 2014). There are also a few FRBs that appear to have no polarisation (Kumar et al., 2019; CHIME/FRB Collaboration et al., 2022), but this might not be intrinsic. Feng et al. (2022) reported a trend where linear polarisation was found to be lower at lower frequencies for a sample of repeating FRBs, and while this could be an intrinsic effect, it is possibly due to rotation measure (RM, Section 1.2.3) scattering, which would then cause depolarisation at lower frequencies and could explain why some FRBs appear not to be polarised.

The polarisation position angle (PPA) refers to the orientation of the electric field vector of an electromagnetic wave, and describes the direction of oscillation of the electric field. For most FRBs, both repeating and non-repeating, the PPA appears flat, meaning that for each burst, it remains constant (e.g. Michilli et al. 2018). However, there are several repeating and non-repeating FRBs which exhibit PPA swings: the repeating FRB 20180301A, for example, displays a PPA that changes between successive bursts, as well as PPA swings over the course of the individual bursts themselves (Luo et al., 2020). FRB 20181112A is a multi-component non-repeater which displays PPA variations within each individual component, as well as from one component to the next (Cho et al., 2020). Jiang et al. (2022) showed that for the repeating

FRB 20201124A, the PPA appears flat for about two thirds of the bursts, while the other third display significant variations in PPA. These examples illustrate the variety of PPA behaviors observed in FRBs, ranging from consistently flat profiles to significant swings, both within and between bursts.

1.5 Current FRB population

As mentioned in Section 1.3, the current FRB population at the time of writing consists of more than 700 FRBs, and out of these, approximately 60 are repeaters. The DMs of discovered FRBs range from a minimum of 87.82 pc cm^{-3} for the repeating FRB 20200120E (Bhardwaj et al., 2021; Kirsten et al., 2022), to a maximum of 3338 pc cm^{-3} for FRB 19920913A (Crawford et al., 2022). The furthest reported FRB is FRB 20230521B, at a redshift of $z = 1.354$ (Connor et al., 2024), although this is not yet confirmed, as the redshift was estimated from a single line which was assumed to be $\text{H}\alpha$. The previous furthest reported redshift for a FRB was $z = 1.016 \pm 0.002$ for FRB 20220610A (Ryder et al., 2023). As mentioned in Section 1.4.2, the lowest frequency at which a FRB has been detected is 110 MHz for FRB 20180916B (Pastor-Marazuela et al., 2021; Pleunis et al., 2021), while FRB 20121102A has been detected at up to 8 GHz (Gajjar et al., 2018), which is the highest frequency at which any FRB has been detected and which, when taking redshifting into account, is actually closer to 10 GHz in the source frame. FRBs exhibit a wide range of RMs. For example, FRB 20121102 has a RM that is immensely high (above 10^5 rad m^{-2} in 2017; Michilli et al. 2018), and that varies greatly, with a decrease in the value of its RM of about 15 per cent per year (Hilmarsson et al., 2021). On the other hand, FRBs 20150215A and 20150807A have RMs as low as $\sim 10 \text{ rad m}^{-2}$ (Petroff et al., 2017; Ravi et al., 2016). Pandhi et al. (2024) measured RMs for 89 polarised non-repeating FRBs, and found them to range from $0.5 - 1160 \text{ rad m}^{-2}$. CHIME/FRB Collaboration et al. (2021) suggest that, in their catalog of 536 FRBs, a large number of these have scattering timescales greater than 10 ms, but many went undetected due to the difficulty of measuring a narrow burst when strong scattering is present. Nimmo et al. (2025) found evidence of scintillation in the spectrum FRB 20221022A, originating both from within the Milky Way and from the FRB’s host galaxy or local environment. This allowed them to constrain the size of the FRB’s emission region to $\lesssim 3 \times 10^4 \text{ km}$, which supports models where the emission comes from within or just beyond the magnetosphere of a compact object (FRB emission mechanism models are discussed in detail in Section 1.7). Out of the approximately 90 FRBs that have been localised to host galaxies so far³, many of them are found in star-forming galaxies (e.g. Heintz et al. 2020; Gordon et al. 2023; Bhardwaj et al. 2024), and, where their hosts have been found to be spiral galaxies, there also seems to be a tendency for them to be located in the galaxy’s spiral arms (Mannings et al., 2021). Some FRBs have also been localised to low-metallicity dwarf galaxies (e.g. Tendulkar et al. 2017), and one FRB has been localised to a globular cluster (Kirsten et al., 2022). Two repeating FRBs have been associated with persistent radio sources (Chatterjee et al., 2017; Niu et al., 2022).

1.6 Progenitor models

Since the discovery of FRBs, a large number of models have been proposed to explain what causes them. As of now, we do not have an answer as to which of these models is/are correct, but there are certain models that are generally more accepted than others. The current models can be put into general groups, and an overview of the various models is given in this Section.

³The FRB Community Newsletter (Volume 5, Issue 12, DOI: 10.7298/A61P-WA30).

When I discuss progenitor models, I am referring to models that explain what astrophysical object or system produces the conditions for a FRB to occur.

1.6.1 Isolated neutron star models

When nuclear fusion halts in a star which had an initial mass between approximately 8 and $25 M_{\odot}$, the star goes supernova, whereby its core collapses in on itself and the star’s outer layers are expelled. What is left behind is a dense core around 20 km in diameter, with a mass of around 1.4 times that of the Sun, and that is supported by both neutron degeneracy pressure and the nuclear Strong force at short distances. This extremely dense remaining core is a neutron star (NS), and due to the conservation of angular momentum as the progenitor star collapses, neutron stars rotate extremely fast, with spin periods of non-recycled NSs ranging from tens of milliseconds to tens of seconds. The existence of neutron stars was first proposed by Baade & Zwicky (1934) and was confirmed by the discovery of the first pulsar by Jocelyn Bell Burnell in 1968 (Hewish et al., 1968). Pulsars are rapidly rotating neutron stars that emit beams of electromagnetic radiation from their magnetic poles. We are able to observe pulsars if they are oriented such that their beams of radiation sweep across our line of sight, in a similar way to how ships see lighthouses at sea.

A magnetar (Duncan & Thompson, 1992) is a neutron star with a magnetic field exceeding $\sim 10^{14}$ G. They are magnetically powered NSs, and some NSs which exhibit magnetar-like activity appear to have relatively low dipolar magnetic fields (10^{12-13} G, e.g. Turolla & Esposito 2013). Magnetars are observed as Soft Gamma Repeaters (SGRs; Norris et al. 1991) and Anomalous X-ray Pulsars (AXPs; Fahlman & Gregory 1981; van Paradijs et al. 1995; Mereghetti & Stella 1995; Mereghetti 2001). The current Galactic magnetar population consists of 16 SGRs and 14 AXPs⁴. SGRs are NSs that emit sporadic bursts of gamma-rays and X-rays. The energies of the emitted gamma-rays are low, hence the term “soft”. AXPs are X-ray pulsars with slow rotation periods, in the range of $\sim 2 - 12$ s, and large magnetic fields.

Several models propose that isolated neutron stars are the progenitors of FRBs, and out of these, a few specifically invoke magnetars. Neutron stars are considered as candidate progenitors to FRBs for several reasons; they emit across similar regions of the electromagnetic spectrum, and the short timescales of FRBs imply that they are emitted from compact regions. Additionally, their immense luminosities could indicate that they are powered by the vast magnetic energy reserves in magnetar magnetospheres. The large rotation measures displayed by FRBs (Michilli et al., 2018), as well as the sad trombone effect (e.g. Hessels et al. 2019), and their polarisation position angle swings across bursts (Luo et al., 2020), are all possible to explain in magnetar models. Additionally, when Thornton et al. (2013) reported the first FRBs after the initial “Lorimer burst”, they inferred a FRB rate which was consistent with the rate of SGR flares.

Pulsars have also been suggested in some models as being the progenitors to FRBs. Some young pulsars, like the Crab pulsar, emit giant pulses (Eilek & Hankins, 2016), and several authors have suggested that an intensified version of this process could power FRBs (Cordes & Wasserman, 2016; Lyutikov et al., 2016). In general, however, FRBs have luminosities that are $\sim 10^{12}$ times greater than those of pulsar pulses (Nimmo et al., 2022).

Further support for magnetars as progenitors for FRBs came about when a bright burst of radio emission (CHIME/FRB, 2020; Bochenek et al., 2020) was observed from the Galactic magnetar SGR 1935+2154 (Cummings et al., 2014; Lien et al., 2014; Israel et al., 2016), which is sometimes called the first “Galactic” FRB. The reason that it is not definitively deemed

⁴<https://www.physics.mcgill.ca/pulsar/magnetar/main.html>

to be a FRB is because the burst was still ~ 30 times less energetic than the least energetic known FRB at the time. Nevertheless, the detection of a bright burst associated with SGR 1935+2154 still brought us closer to bridging the gap between magnetars and FRBs, as it was $\sim 4 \times 10^3$ more energetic than any pulses from the Crab pulsar, which up until that point had produced the brightest radio bursts within our Galaxy on such timescales. In the weeks that followed, weaker radio pulses from SGR 1935+2154 were seen (Zhang et al., 2020; Kirsten et al., 2021). Beniamini et al. (2020) suggested that Ultra-Long Period Magnetars (ULPMs) could be progenitors to FRBs 20180916B and 20121102A, and two recently discovered ULPMs (Hurley-Walker et al., 2022; Caleb et al., 2022) provide some support for this theory. All in all, there is growing evidence in support of magnetars being the progenitors of at least some FRBs, and they are generally the most favoured out of the many proposed models.

1.6.2 Interacting compact object models

There are several FRB progenitor models which suggest that FRBs result from interactions between compact objects and an external influence, such as with their surrounding environments, with binary companion objects, or with orbiting objects.

Neutron stars, introduced in Section 1.6.1, are not the only compact objects which are proposed to produce FRBs; white dwarfs (WDs) and black holes (BHs) have been suggested as well, although, since they do not have the strong magnetic fields associated with NSs, the method by which they produce FRBs would rely on interactions with other objects or media. WDs and BHs are both stellar remnants left behind after stars die, just as NSs are. WDs are left behind after stars with initial masses $< 8 M_{\odot}$ become unable to fuse elements heavier than C and O in their cores. The outer layers of the star are expelled, and what is left behind is a white dwarf, which is supported by electron degeneracy pressure and which has a mass below $1.4 M_{\odot}$. A black hole is the remnant of a star of initially more than $25 M_{\odot}$. Black holes are too massive to be supported by neutron degeneracy pressure, and they possess gravitational fields so strong that not even light is able to escape from them. WDs are not typically thought of as being likely progenitors to FRBs when compared with NSs, as their magnetic fields tend to be lower (although the magnetic moment of a WD can be higher than that of a NS), their rotation periods slower, and they are less dense. Nevertheless, Gu et al. (2016, 2020) suggested a model where FRB emission is produced via magnetic reconnection in a compact NS-WD binary in which the WD has overfilled its Roche lobe, leading to its matter being accreted onto the NS. These are called ultracompact X-ray binaries (e.g. Nelemans & Jonker 2010).

Several authors have proposed models where FRBs are produced due to interactions between a NS and a comet or asteroid (Bagchi, 2017; Dai et al., 2016; Dai, 2020; Dai & Zhong, 2020; Geng & Huang, 2015; Smallwood et al., 2019). It has also been suggested that FRBs could be produced just before a binary neutron star merger takes place (e.g. Wada et al. 2020; Wang et al. 2016). This would hypothetically arise due to a neutron star with a weak magnetic field moving through the magnetosphere of a second neutron star that possesses a stronger magnetic field. Zhang (2020) argued that repeating FRBs could be produced via magnetic reconnection due to strong magnetospheric interactions between two neutron stars shortly before a merger takes place. There are also a few models which invoke supermassive black holes (SMBHs) - black holes with masses of more than $10^5 M_{\odot}$ - or active galactic nuclei (AGN). These were prompted by the fact that two repeating FRBs, FRB 20121102A and FRB 20190520B, are associated with persistent radio sources which could be AGN (Chatterjee et al., 2017; Niu et al., 2022). Vieyro et al. (2017) suggested that FRBs could be caused by the interaction between an AGN jet and a surrounding cloud of material. Another AGN scenario suggests that, as it travels through

magnetised regions of plasma surrounding a SMBH, a NS can produce FRB-like bursts via magnetic reconnections (Zhang, 2017; Zhang, 2018a). This model would also work to explain the large RM and persistent radio sources associated with FRBs 20121102A and 20190520B.

1.6.3 Cataclysmic models

Cataclysmic models have been suggested to explain FRBs, but were ruled out as being able to explain all FRBs once some were observed to repeat. Additionally, the rates of cataclysmic events are too low to explain all FRBs (e.g. Ravi 2019). If repeating and non-repeating FRBs have different underlying mechanisms, then it could be the case that non-repeating FRBs are caused by cataclysmic events, while repeating sources have a different, sustained origin, although it cannot be definitely said that one-off FRBs will never repeat. The cataclysmic models suggested to invoke FRBs are mostly compact object mergers, as well as a model which proposes that the implosion of hypothetical supramassive neutron stars (SMNSs) is responsible for FRBs.

Falcke & Rezzolla (2014) suggested that “blitzars” could be the progenitors to FRBs; the term, coined by the authors, refers to the process whereby closed magnetic field lines of a SMNS are ejected as the neutron star suddenly collapses to a BH. The collapse would occur because SMNSs are supported by their spin; their non-spinning masses surpass the maximum allowed mass for neutron stars, and they would collapse into BHs once their rotation slowed down and they could no longer be supported against gravity.

In NS-NS merger models, it is suggested that FRBs are produced just before the merger takes place due to interactions between the magnetospheres of the two NSs (e.g. Hansen & Lyutikov 2001; Piro 2012; Lai 2012; Totani 2013; Wang et al. 2016). WD-WD mergers have also been proposed to explain FRBs, with Kashiyama et al. (2013) hypothesising that short bursts of radio emission could be produced by the magnetised WD that forms as a result of the merging of two WDs. In this model, the FRB could be an accompaniment to a type Ia supernova, meaning that there could be observable optical emission. In NS-BH merger models, it is suggested that radio emission could be produced when the BH becomes charged due to interaction with the NS’s magnetic field (e.g. Levin et al. 2018; McWilliams & Levin 2011; Mingarelli et al. 2015). In the case of NS-NS mergers, it has been hypothesized that there could be observable optical emission from an ensuing kilonova (e.g. Metzger et al. 2010).

1.6.4 Exotic models

There are several FRB models which do not fall within the previous categories, and/or that invoke hypothetical objects or phenomena that have not been supported by observations to explain FRBs. These are called exotic models. It has been suggested that stars made up of quarks, called strange quark stars, could be behind FRBs. Ouyed et al. (2020a,b) proposed that FRBs can be explained by quark novae produced when a NS becomes a quark star. It has also been suggested that FRBs are produced by superconducting cosmic strings (e.g. Vachaspati 2008). Primordial black holes, which are hypothetical BHs formed right after the Big Bang, are proposed to produce FRBs via interaction with NSs (Abramowicz et al., 2018). Iwazaki (2015, 2021) suggested that FRBs are caused by axion stars, which are stars made up of the hypothetical axion particle. The model proposes that collisions between axion stars NSs could produce FRBs. Perhaps the most extreme model is that suggested by Lingam & Loeb (2017), who propose that FRBs are produced by extragalactic civilisations.

1.7 Emission mechanisms

The observed properties of FRBs, such as the short timescales and luminosities which range from $\sim 10^{38} - 10^{46} \text{ erg s}^{-1}$, require that they are powered by coherent emission, which is when the emitted waves have a consistent phase relationship with one another and the radiation intensity scales as the square of the number of emitting particles. The main models that would be able to account for the emission observed from FRBs fall into two categories: those invoking compact object magnetospheres, and those invoking the synchrotron maser mechanism in relativistic shocks. When I discuss emission mechanisms, I am referring to the physical process by which the observed coherent radio burst is produced.

1.7.1 Models invoking compact object magnetospheres

Ruderman & Sutherland (1975) suggested that pulsar radio emission is coherent curvature radiation from the inner magnetosphere generated by electron-positron pairs, which are produced in “sparks”, which travel along the pulsar’s magnetic field lines. The model accounts for the coherent radio emission in pulsars, but cannot explain how coherence would be maintained (Melrose, 1978), although Melikidze et al. (2000) suggested that this problem could be overcome by a soliton model. Several authors have discussed how the model could be used to explain FRB emission (e.g. Katz 2014; Yang & Zhang 2018; Lu & Kumar 2018; Lu et al. 2020; Cooper & Wijers 2021). Wang et al. (2019) suggest how such a model could explain the sad trombone effect displayed by repeaters, proposing that sub-pulses which arrive later are emitted from regions with less-curved magnetic field lines, resulting in progressively lower-frequency emission. Another pulsar model which has been suggested as being applicable to FRB emission, is the one already mentioned in Section 1.6.1, whereby FRBs are emitted via an intensified version of giant pulses from pulsars. Nimmo et al. (2022) showed that the repeating FRB 20200120E is able to produce bursts of radio emission on timescales as short as $\sim 60 \text{ ns}$, and with brightness temperatures comparable to “nano-shots” from the Crab pulsar, providing support for the theory that at least repeating FRBs could be produced similarly to giant pulses from pulsars. Figure 1.3, taken from Lu et al. (2020) presents a diagram of the proposed model discussed in that paper.

Flares in magnetar magnetospheres have also been proposed to explain the coherent emission seen from FRBs (Katz, 2016; Kumar et al., 2017; Lu & Kumar, 2018; Wadiasingh & Timokhin, 2019; Kumar & Bošnjak, 2020; Lyutikov & Popov, 2020), given that they can emit bursts of bright radio emission when they are highly active. In such models, FRB emission comes from close to the surface of the magnetar, due to forced magnetic reconnection as a result of repeated outbursts. As mentioned in Section 1.6.1, the bright burst of radio emission from SGR 1935+2154 provides support for this theory. Magnetospheric models do predict a high-energy counterpart to FRBs (e.g. Cooper & Wijers 2021; Yang & Zhang 2021).

1.7.2 Models invoking the synchrotron maser mechanism

As opposed to FRBs being produced close to the surface of a magnetar, synchrotron maser models suggest that the coherent emission from FRBs is produced far away from the magnetar surface, due to synchrotron maser emission caused by magnetised shocks (Beloborodov, 2017; Metzger et al., 2019; Beloborodov, 2020). In such models, a magnetar is predicted to produce relativistic outflows that then shock the surrounding medium. There are several versions of the synchrotron maser model: in the vacuum synchrotron maser model (Ghisellini, 2016), plasma effects are not taken into account, although in reality the conditions required to produce an

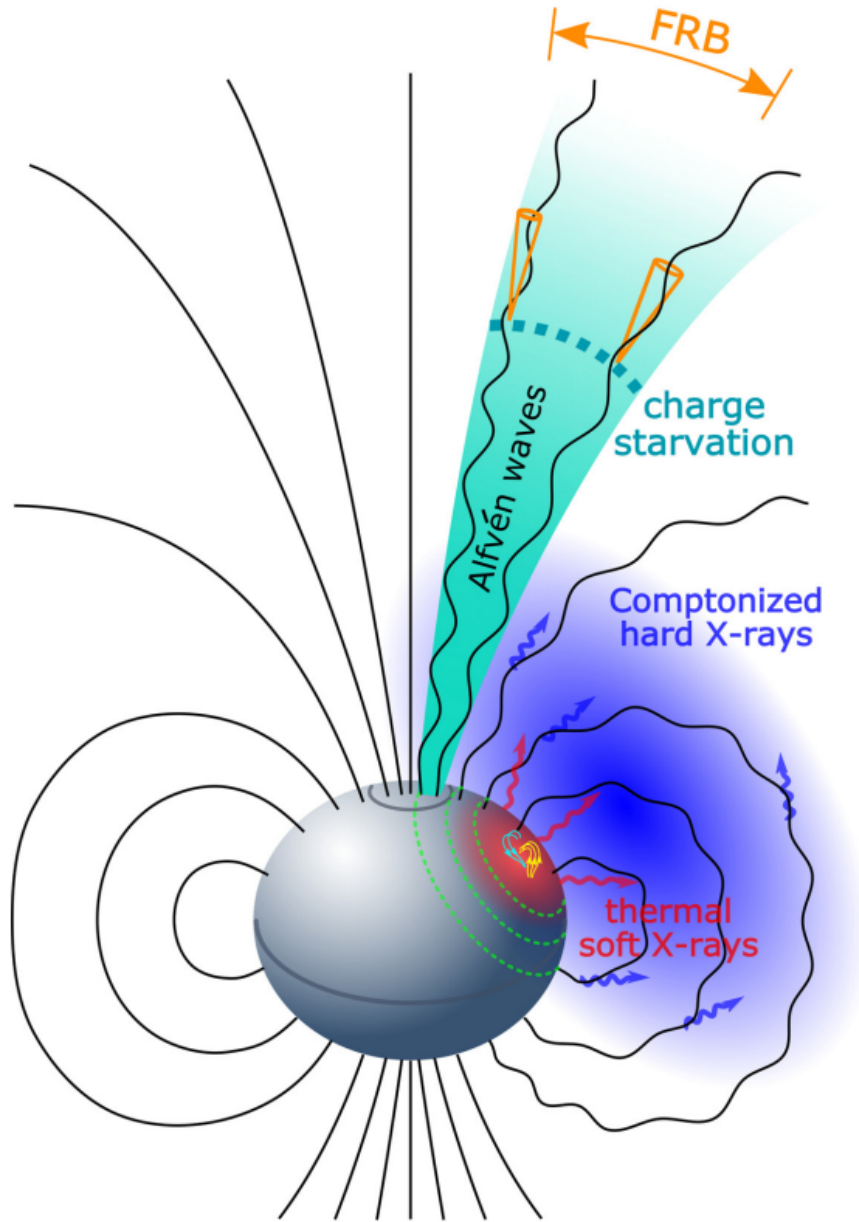


Figure 1.3: Magnetospheric model described in Lu et al. (2020). Figure taken from Lu et al. (2020).

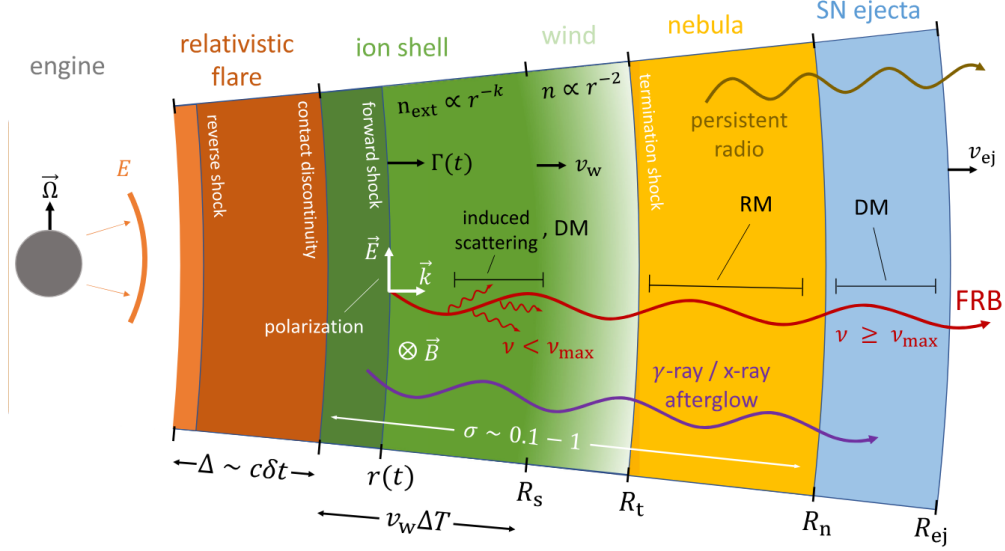


Figure 1.4: Synchrotron maser model described in Metzger et al. (2019). Figure taken from Metzger et al. (2019).

FRB in such a model would likely not be met. Figure 1.4, taken from Metzger et al. (2019), shows a diagram of the synchrotron maser model proposed in that paper.

Other models do include plasma effects. FRBs have been proposed to originate from a plasma synchrotron maser in non-magnetised relativistic shocks, where the plasma and the central engine are both weakly magnetised (Long & Pe’er, 2018). The issue with this is that, due to the weak magnetisation, the high levels of polarisation observed in FRBs cannot be explained. Alternatively, FRBs have been proposed to originate from synchrotron emission produced by highly magnetised relativistic shocks. In such models, the central engine is a flaring magnetar (Beloborodov, 2017; Metzger et al., 2019; Beloborodov, 2020), whose flares generate shocks in the surrounding magnetised medium. These shocks propagate outward, amplifying the surrounding magnetic fields and resulting in a synchrotron maser that coherently propagates outward in the form of an FRB. This model would account for the high linear polarisation that is seen in many FRBs, as well as explaining the sad trombone effect, since the decelerating shocks over time would result in radio signals drifting downwards in frequency (Metzger et al., 2019). It could also explain the persistent radio sources observed to be associated with FRB 20121102A and FRB 20190520B mentioned in Section 1.6.2 (e.g. Sridhar et al. 2021). This model, as well as being generally favoured as a possible explanation for at least some FRBs, also predicts a multi-wavelength afterglow shortly after the FRB (e.g. Metzger et al. 2019; Margalit et al. 2020; Cooper et al. 2022). However, one difficulty with this model is that it does not explain the variability of FRB 20180916B on microsecond timescales (Nimmo et al., 2022), nor does it appear consistent with the 30 ms separation between the burst components of the “Galactic” FRB from SGR 1935+2154 (CHIME/FRB, 2020; Cooper et al., 2022).

1.8 Justification for an optical counterpart search

No counterpart at a non-radio wavelength has been detected for any FRB (with the exception of the hard X-ray burst that accompanied SGR 1935+2154; Mereghetti et al. 2020), which is a problem when it comes to ruling out the many models that try to explain their origins. Out of the many progenitor models, some predict counterparts at other wavelengths, and on varying timescales. As such, the detection of any counterpart would be helpful in narrowing down the

long list of models that exist. Considering optical counterparts in particular, some models predict no counterpart, some predict bright ($\gtrsim 10^{41} \text{ erg s}^{-1}$) afterglows on very short (millisecond) timescales, and others predict fainter ($\lesssim 10^{39} \text{ erg s}^{-1}$) afterglows on longer timescales (minutes to hours) (e.g. Lyubarsky 2014; Lyutikov & Lorimer 2016; Beloborodov 2017; Metzger et al. 2019; Yang et al. 2019; Beloborodov 2020; Margalit et al. 2020). Yang et al. (2019) predict a fast optical burst (FOB) that is produced at the same time as the FRB via inverse-Compton scattering. As discussed in Section 1.6, magnetar models are generally favoured when it comes to explaining the origins and emission of FRBs, and the synchrotron maser model predicts a multi-wavelength afterglow. As such, the detection of an optical counterpart could, for example, provide further support and constraints for FRBs resulting from synchrotron maser emission, while ruling out models which predict no optical or multi-wavelength emission. Another significant justification for undertaking our research is that searching for any kind of counterpart to FRBs is not a simple task: they last for only a few milliseconds, and then they are gone. Of course, some have been observed to repeat, but the vast majority have only been seen once. For these once-off events, a radio astronomer who discovers a new FRB cannot quickly get in touch with someone at, for example, an optical telescope, and ask them to point their telescope at the coordinates of the FRB in the hopes of seeing something; by that time it is far too late. Even automated alert systems would not result in follow-up observations happening fast enough, and moreover, if both wavelengths are emitted simultaneously at the source, we would actually expect the optical emission to arrive before the radio emission, due to dispersion effects. As a result of this, most of the attempts at finding multiwavelength counterparts to FRBs have been focused on repeating FRBs. In such cases, the location of the FRB is known, and it is much easier to coordinate simultaneous radio observations with observations at other wavelengths. The only way to obtain simultaneous observations at other wavelengths of random, once-off FRBs, would be if one had a system of two telescopes - one radio and one at a different operating wavelength range - that was dedicated to observing simultaneously across both wavelength ranges. This would greatly increase the chances of simultaneously observing the coordinates of any kind of FRB - repeating or not - in multiple wavelengths, and as such, getting closer to the answer of whether or not counterparts at other wavelengths exist. This, in turn, would contribute towards resolving the currently unanswered question of what exactly causes FRBs. Such systems are very rare, but one that exists in the world consists of the MeerKAT radio array and the MeerLICHT optical telescope, both of which are described in further detail in Chapter 2.

1.9 Previous searches for counterparts

There have been numerous attempts at searching for emission associated with FRBs in other parts of the electromagnetic spectrum. Most of these searches have focused on repeating FRBs (e.g. Hardy et al. 2017; MAGIC Collaboration et al. 2018; Niino et al. 2022; Hiramatsu et al. 2023; Kilpatrick et al. 2021; Kilpatrick et al. 2023; Trudu et al. 2023), since these are much easier to try and observe simultaneously in radio and other wavelengths, however, there have been some attempts which have also looked at non-repeaters (e.g. Hiramatsu et al. 2023; Núñez et al. 2021).

Hardy et al. (2017) conducted simultaneous observations of the repeating FRB 20121102, located at a redshift of $z = 0.19$ (Tendulkar et al., 2017), using the 100-m Effelsberg Radio Telescope and ULTRASPEC, mounted on the 2.4-m Thai National Telescope (Dhillon et al., 2014). During their observations, they detected 13 bursts in the radio band and stacked the optical data around the arrival time of each burst. This analysis yielded an optical fluence

limit of 0.17 Jy ms over a timescale of 141.4 ms, after correcting for MW dust extinction. The resulting optical-to-radio fluence ratio limit was constrained to $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.28$.

The MAGIC Collaboration et al. (2018) carried out radio, optical, and very-high-energy (VHE) gamma-ray observations of FRB 20121102 simultaneously, making use of the Arecibo radio telescope and the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope, located on La Palma in the Canary Islands. As the MAGIC telescopes are primarily designed for VHE gamma-ray detection, whereby they detect Cherenkov light from gamma-rays entering the atmosphere, they are equipped with an optical capability. The authors detected five radio bursts and stacked the optical data around the arrival times of the bursts, thereby deriving optical fluence limits of 0.025 Jy ms on a timescale of 0.1 ms, 0.086 Jy ms on a timescale of 1 ms, 0.25 Jy ms on a timescale of 5 ms, and 0.36 Jy ms on a timescale of 10 ms. These limits were all corrected for MW dust extinction and correspond to optical-to-radio fluence ratio limits of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.013 - 0.18$.

Niino et al. (2022) conducted optical observations of the repeating FRB 20190520B (redshift $z = 0.24$, Niu et al. 2022) using Tomo-e Gozen (Sako et al., 2018), a high-speed camera on the Kiso 105-cm Schmidt telescope at Kiso Observatory in Japan. Simultaneous radio observations were performed with the Five-hundred-meter Aperture Spherical Telescope (FAST). They detected 11 radio bursts but found no associated optical emission, deriving MW-dust-extinction-corrected optical fluence limits as deep as 0.068 Jy ms over a 40.9 ms timescale for individual bursts, with a deeper limit of 0.029 Jy ms obtained by averaging the optical flux of all 11 bursts. Longer timescale analyses yielded fluence limits of 0.13 Jy ms on a 0.45 s timescale, and 0.34 Jy ms on a 2.1 s timescale. These constraints correspond to optical-to-radio fluence ratio limits of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.23 - 2.1$ for individual bursts and $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.20$ for the stacked limit.

Hiramatsu et al. (2023) conducted simultaneous, follow-up, and archival survey observations of 15 well-localised FRBs, including 7 repeaters, 7 non-repeaters, and SGR 1935+2154. For the repeater FRB 20220912A (redshift $z = 0.077$, Ravi et al. 2023), they obtained a nearly simultaneous 15 s observation with Binospec (Fabricant et al., 2019) on the 6.5 m MMT Observatory in Arizona, USA. This set a fluence ratio limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.00010$ over a ~ 0.4 s timescale. Additional observations of this FRB were conducted using KeplerCam (Szentgyorgyi et al., 2005) on the 1.2 m Telescope at the Fred Lawrence Whipple Observatory and the Sinistro camera on the 1 m telescope at the McDonald Observatory, part of the Las Cumbres Observatory (LCO; Brown et al. 2013a) network. The Binospec observations yielded a luminosity limit of $\nu L_{\nu} \sim 2 \times 10^{41} \text{ erg s}^{-1}$. Simultaneous observations with KeplerCam and LCO provided luminosity limits ranging from $\sim (0.3 - 2.9) \times 10^{42} \text{ erg s}^{-1}$. The authors reported these luminosity limits as the deepest for an extragalactic FRB to date, and their limits correspond to fluence ratio constraints as deep as $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.0010$.

Kilpatrick et al. (2023) utilised the ‘Alopeke high-cadence camera (Scott, 2018; Scott et al., 2021) on the Gemini North telescope at Mauna Kea, Hawaii, to perform optical observations of two bursts from the repeater FRB 20180916B (redshift $z = 0.034$, Marcote et al. 2020). These observations were conducted simultaneously with radio observations by CHIME. They derived optical fluence limits, corrected for MW dust extinction, on ~ 10.4 ms timescales for each burst, placing constraints on the optical-to-radio fluence ratio of $F_{\text{opt}}/F_{\text{radio}} < 0.002 - 0.007$.

Trudu et al. (2023) conducted an extensive multi-wavelength campaign on FRB 20180916B, spanning 8 months. Their radio observations utilised the Sardinia Radio Telescope (SRT) and the upgraded Giant Metrewave Radio Telescope (uGMRT; Gupta et al. 2017). Optical observations were performed with various instruments, including the Aqueye+ fast photon

counter (Barbieri et al., 2009; Zampieri et al., 2015) on the Copernicus telescope, and the IFI+Iqueye fast photon counter (Naletto et al., 2009) on the Galileo telescope, both based in Asiago. Additional observations were carried out with the Calar Alto 2.2 m telescope, the 2.5 m telescope at the Caucasian Mountain Observatory (CMO) of the Sternberg Astronomical Institute (SAI), and the SiFAP2 fast photometer (Ghedina et al., 2018; Ambrosino et al., 2016) on the 3.6 m Telescopio Nazionale Galileo (TNG) in the Canary Islands. Aqueye+ provided simultaneous optical fluence limits of 0.005 Jy ms on a 200 ms timescale and 0.009 Jy ms on a 30 s timescale in November 2020, and 0.005 Jy ms (200 ms) and 0.008 Jy ms (30 s) in August 2021. IFI+Iqueye yielded upper limits of 0.09 Jy ms (200 ms) and 0.13 Jy ms (30 s), while TNG reported 1.02 mJy ms (200 ms) and 1.56 mJy ms (30 s). These upper limits, none of which were corrected for MW extinction, constrain the energy ratio to $E_{\text{opt}}/E_{\text{radio}} < 1.3 \times 10^2 - 7.8 \times 10^2$, representing the most stringent upper limits for FRB 20180916B to date.

All of the limits discussed above were for known repeating FRBs. Hiramatsu et al. (2023) did also look at archival data for non-repeating FRBs, but did not have any close to simultaneous observations of non-repeaters. Additionally, none of the studies discussed have systems that are specifically dedicated to observing simultaneously at all times, meaning there is no ongoing effort to try and find an optical counterpart to non-repeating FRBs. Since the majority of FRBs are non-repeaters, and since it is not known whether or not repeaters and non-repeaters are even caused by the same underlying mechanism(s), this means that there is an unexplored area of study, which is that of consistently observing simultaneously in at least two wavelengths (radio and one other) in order to find multi-wavelength counterparts to the various kinds of FRBs: repeating and non-repeating.

Chapter 2

Instruments

2.1 MeerKAT and MeerTRAP

MeerKAT (Jonas & MeerKAT Team, 2016) is an array of radio antennas, located in the Karoo near the town of Carnarvon in South Africa. It consists of 64 dishes, each with a diameter of 13.5 m, and has a maximum possible baseline of 8 km. It has 3 available observing bands, namely the UHF, the *L*-band, and the *S*-band. The UHF covers a wavelength range of 544 – 1088 MHz, the *L*-band covers 856 – 1712 MHz, and the *S*-band spans a range from 1750 – 3500 MHz.

There are several backends on MeerKAT that allow users to conduct specific research using the array. One such backend is MeerTRAP, which consists of the Transient User Supplied Equipment (TUSE; Caleb et al. 2020) and the Filterbanking Beamformer User Supplied Equipment (FBFUSE; Chen et al. 2021; Barr 2017). MeerTRAP stands for Meer(More) TRAnsients and Pulsars, and it is the backend used to search for FRBs. TUSE searches for single pulses, and FBFUSE coherently combines the signals from MeerKAT’s dishes, and is able to form up to 768 coherent beams (CBs) within MeerKAT’s primary beam. The CBs are very sensitive, and have a total field of view (FoV) of $\sim 0.4 \text{ deg}^2$ at 1284 MHz. An incoherent beam (IB) is formed by summing the signals from all of the antennas, and this has the same FoV as MeerKAT’s primary beam, which is $\sim 1 \text{ deg}^2$ at 1284 MHz. The sensitivity of the CBs is about 5 times greater than that of the IB, although this varies depending on the observing frequency and elevation, since the shapes of the CBs change depending on the projection of the array on the sky (Chen et al., 2021; Rajwade et al., 2022). An example of FBFUSE CB tilings can be seen in Figure 2.1, taken from Chen et al. (2021).

AstroAccelerate (Adámek & Armour, 2016) is a GPU-based single pulse search pipeline, which is used to perform a real-time search for bright bursts from each beam, by de-dispersing the data at 1284 MHz in the DM range of 0 pc cm^{-3} to a maximum of $2500 - 5000 \text{ pc cm}^{-3}$. De-dispersion is a process whereby trial DMs are applied to the data, and the correct DM is the one which maximizes the signal-to-noise ratio (S/N). The Inter-Quartile Range Mitigation (IQRM; Morello et al. 2021) algorithm is applied to reduce the number of detections that occur due to radio frequency interference (RFI).

Once a burst has been confirmed as a genuine transient, a transient buffer (TB) data dump is triggered, whereby high resolution complex voltage data from around the time of the burst are stored on the FBFUSE cluster. The TB data dump triggers are sent using VOEvent alerts. The TB system is described in detail in Rajwade et al. (2024), and Figure 2.2, taken from Rajwade et al. (2024), visualises the pipeline.

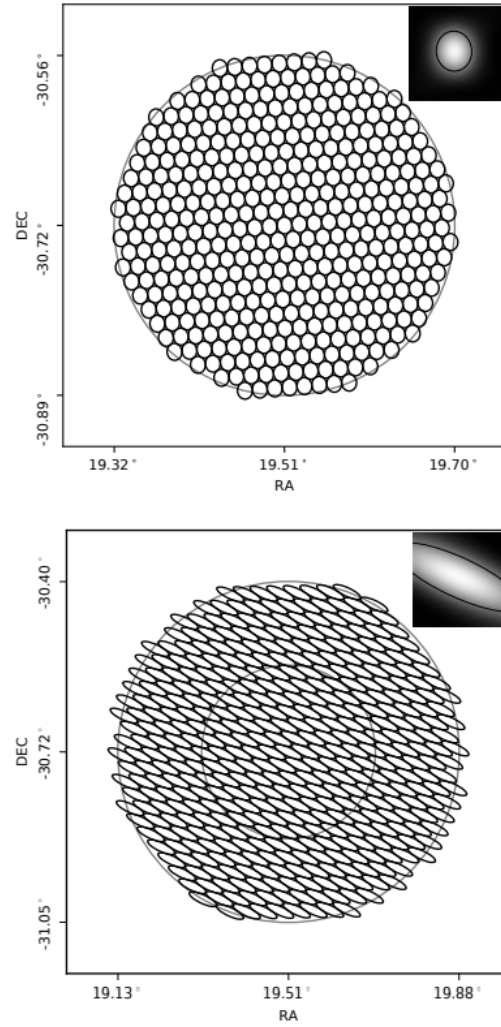


Figure 2.1: In the two panels above, the outer grey circle represents the region within which the CBs have been formed, while the smaller black ellipses show the CBs. In the top panel, the array is pointing at zenith, while in the bottom panel, it is pointing near the horizon, and the described variation in CB shapes depending on observing elevation can be seen. In the top panel, 405 CBs have been formed, while there are 409 CBs in the bottom panel. Figure taken from Chen et al. (2021).

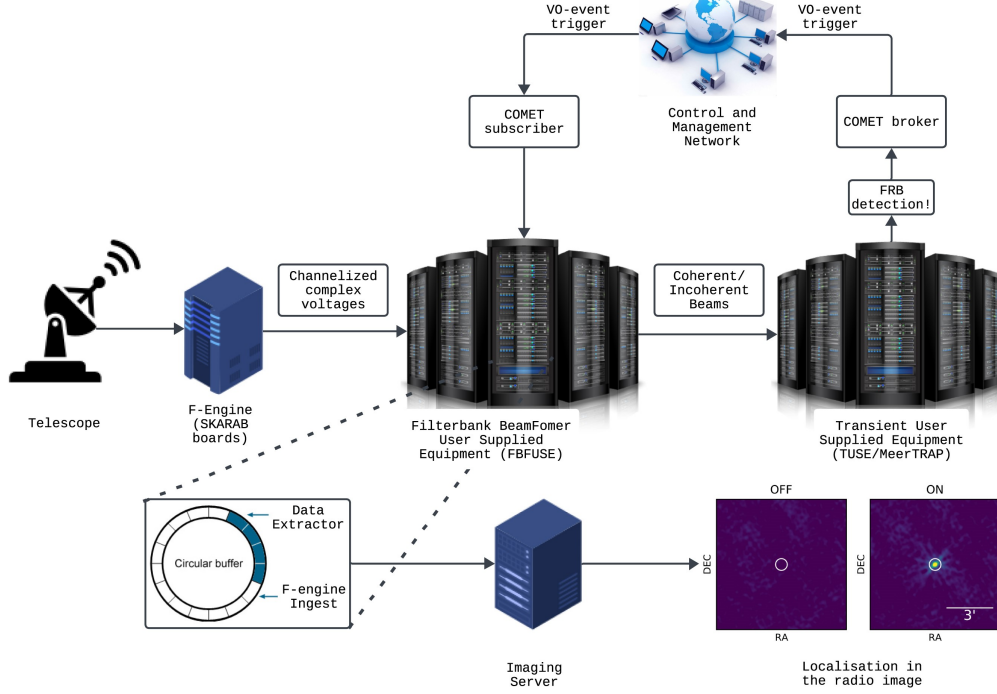


Figure 2.2: MeerTRAP and TB system pipeline. Figure taken from Rajwade et al. (2024).

2.2 MeerLICHT

MeerLICHT is a fully robotic optical telescope located in Sutherland, South Africa. It has a 65 cm primary mirror, and six observing filters: the Sloan Digital Sky Survey (SDSS; York et al. 2000) u , g , r , i and z bands, and a q -band that covers a range of 440 – 720 nm. MeerLICHT was developed as a prototype for the BlackGEM array in Chile, and has a field of view of 2.7 deg^2 (Groot et al., 2024). The declination upper limit for MeerLICHT is $+30 \text{ deg}$, while its pointing limit is $> 20 \text{ deg}$ above the horizon in elevation, and its hour angle (HA) limit is between -3 hours and 4.5 hours (Groot et al., 2024). MeerLICHT’s CCD detector chip has dimensions of 10560×10560 pixels of $9 \times 9 \mu\text{m}$ each, which results in a pixel scale of $0.56''/\text{pixel}$. The telescope is mounted on an equatorial mount, and uses a modified Dall-Kirkham design.

MeerLICHT was commissioned with the goal of co-observing with MeerKAT, and as such, when the above conditions are met, MeerLICHT observes simultaneously with MeerKAT, or otherwise, if syncing cannot be established, it follows a backup program of observing regions of Local Universe mass over-densities, or it follows up on other high priority targets, or it builds up reference images for its survey of the southern sky. MeerLICHT’s standard observing strategy when it is not synced with MeerKAT, is to observe in 1-minute-long exposures in the filter sequence q , u , i , etc. When it is synced with MeerKAT, it still takes 1-minute-long exposures, but in the filter sequence q , g , q , i , q , u , q , r , q , z , q . There are approximately 15 – 25 seconds of overhead time between each MeerLICHT exposure, while the telescope re-points, changes filter, and reads out the image data from the CCD. MeerLICHT conducts observations based on a pre-defined sky grid.

MeerLICHT images are processed using BlackBOX (Vreeswijk & Paterson, 2021a) and ZOGY (Vreeswijk & Paterson, 2021b; Zackay et al., 2016). BlackBOX performs routine CCD reduction procedures on the raw data products, and ZOGY performs source identification, photometry, astrometry, and searches for transient candidates. The classification of transient candidates is based on the image subtraction routine developed by Zackay et al. (2016). A catalogue of

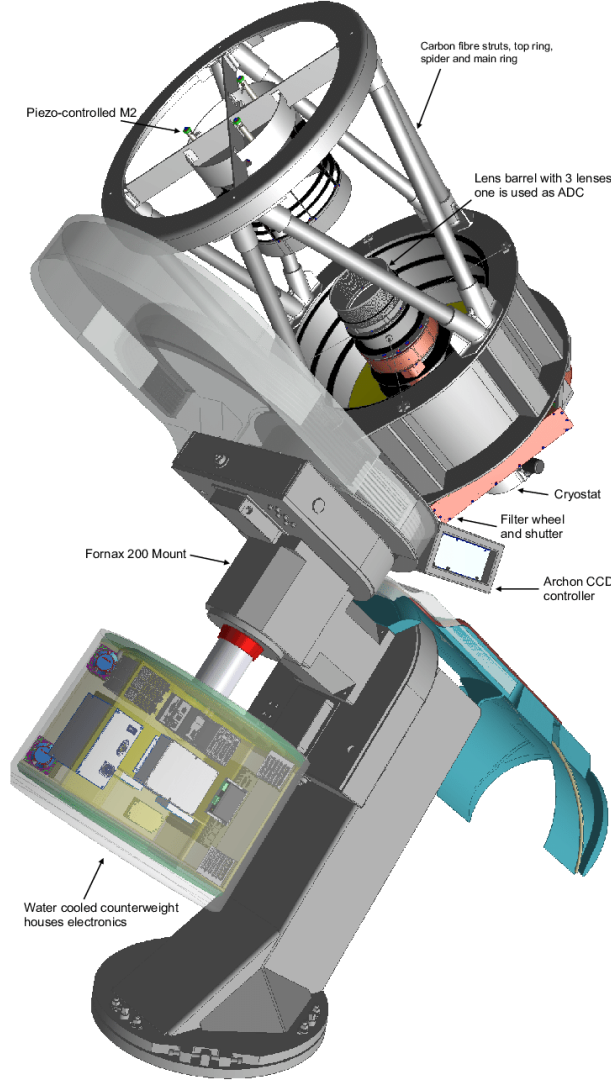


Figure 2.3: MeerLICHT’s telescope design. Figure from Bloemen et al. (2016).

Gaia DR2 (Brown et al., 2018) stars is used for the photometric and astrometric calibration of MeerLICHT images. ZOGY uses **SExtractor** (Bertin & Arnouts, 1996) to detect sources in a given MeerLICHT image, and flux measurements are obtained for sources based on the point spread function (PSF) at the source’s position. The PSF at a given position is determined using **PSFEx** (Bertin, 2011). Once the MeerLICHT images are reduced, they are stored and images and output products can be accessed via **ilifu**, a cloud computing facility hosted at the University of Cape Town, and operated by the Inter-University Institute for Data Intensive Astronomy (IDIA).

2.3 Overview of attempts to simultaneously observe FRBs using MeerLICHT and MeerKAT

Prior to September 2022, MeerLICHT and MeerKAT were not regularly syncing, due to a miscommunication between MeerKAT and MeerLICHT’s schedulers. Since September 2022, however, the two have, for the most part, been syncing at night when it is feasible. As such, for all FRBs discovered by MeerTRAP since September 2022, we searched MeerLICHT’s logs to see whether it happened to be observing simultaneously for any of the FRBs. We found that

this had not been the case up until February 2023, which is when I started this Masters research project. For the duration of the rest of my Masters, whenever MeerTRAP would discover a new FRB, I would check to see whether we had been observing simultaneously with MeerLICHT. For several months we did not obtain any simultaneous observations, for multiple reasons:

- Radio wavelengths can be observed at any time of the day, meaning that some FRBs discovered by MeerKAT were found during daytime, when MeerLICHT wasn't able to be observing.
- Out of the occasions where MeerKAT did find FRBs at night, on some of them MeerLICHT wasn't observing due to unfavourable weather conditions.
- In mid-2023, the town of Sutherland was struck by lightning, and the entire telescope plateau lost power, not only to the telescopes, but to the generators as well. This resulted in about 1 – 2 weeks of lost observing time.

We finally had our first occasion where MeerLICHT and MeerKAT were actually synced at the time of a FRB discovery in August in 2023, although the FRB arrival time was during MeerLICHT's overhead time. Nevertheless, this represented a major breakthrough in our attempt to obtain simultaneous optical-radio FRB data. This is discussed in detail in Chapter 3. After this August 2023 breakthrough, there were several additional close calls:

- On 2024 February 10, MeerTRAP discovered a FRB in the LADUMA (Baker et al., 2018) field, and MeerLICHT was observing, however syncing was not established because the observing block would have gone beyond MeerLICHT's HA limit later in the block. MeerLICHT's scheduler does not sync with MeerKAT if the latter's observing block will eventually result in an HA that is beyond MeerLICHT's limit, even if the limit will only be reached later in the observing block.
- The next night, on 2024 February 11, a FRB was discovered by MeerTRAP at around 20:14:04 UT, also in the LADUMA field. MeerLICHT was syncing with MeerKAT this time, but only up until around five minutes before the FRB's arrival time, at which point MeerLICHT switched over to a different field. The syncing between MeerLICHT and MeerKAT resumed a few minutes after the FRB. This was initially puzzling, but we realised that MeerKAT was delayed by about one minute with respect to its own schedule. MeerLICHT was observing according to MeerKAT's original schedule, and thus starting on each field approximately one minute early. Then, MeerLICHT was ending the observing block five minutes earlier than MeerKAT, and moving to calibrator fields. In the case of the 2024 February 11 FRB, this meant that we just missed the arrival time of the FRB.
- MeerTRAP discovered its first ever repeating FRB on 2024 June 19 in the early hours of the morning. MeerLICHT, however, was not observing that night due to unfavourable weather conditions. Several nights later, MeerKAT re-observed the repeater, and this time, MeerLICHT was observing, however, MeerLICHT's scheduler selected the wrong fixed sky-grid field, and thus no observations of the field of the FRB were obtained. The FRB was observed by MeerKAT for a third time on 2024 June 28, and this time, we were able to schedule MeerLICHT observations of the correct field. The discovery and coordination of optical observations of the repeating FRB are discussed in detail in Chapter 4.

Chapter 3

Contemporaneous optical-radio observations of a fast radio burst in a close galaxy pair

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Abstract

We present the MeerKAT discovery and MeerLICHT contemporaneous optical observations of the Fast Radio Burst (FRB) 20230808F, which was found to have a dispersion measure of $DM = 653.2 \pm 0.4 \text{ pc cm}^{-3}$. FRB 20230808F has a scattering timescale $\tau_s = 3.1 \pm 0.1 \text{ ms}$ at 1563.6 MHz, a rotation measure $RM = 169.4 \pm 0.2 \text{ rad m}^{-2}$, and a radio fluence $F_{\text{radio}} = 1.72 \pm 0.01 \text{ Jy ms}$. We find no optical counterpart in the time immediately after the FRB, nor in the three months after the FRB during which we continued to monitor the field of the FRB. We set an optical upper flux limit in MeerLICHT's q -band of $11.7 \mu\text{Jy}$ for a 60 s exposure which started $\sim 3.4 \text{ s}$ after the burst, which corresponds to an optical fluence, F_{opt} , of 0.039 Jy ms on a timescale of $\sim 3.4 \text{ s}$. We obtain an estimate for the q -band luminosity limit of $\nu L_\nu \sim 1.3 \times 10^{43} \text{ erg s}^{-1}$. We localise the burst to a close galaxy pair at a redshift of $z_{\text{spec}} = 0.3472 \pm 0.0002$. Our time delay of $\sim 3.4 \text{ s}$ between the FRB arrival time and the start of our optical exposure is the shortest ever for an as yet non-repeating FRB, and hence the closest to simultaneous optical follow-up that exists for such an FRB. Our optical upper limits obtained within the first 20 minutes after the FRB are not constraining for the synchrotron maser shock model.

3.1 Introduction

Fast Radio Bursts (FRBs), first discovered in 2007, are bright, millisecond-duration pulses of radio emission. FRBs have dispersion measures (DMs) that are far greater than the expected DM contribution of the Milky Way galaxy, meaning that they are of extragalactic origin. The first FRB was found in archival pulsar data from 2001 which made use of Murriyang, the Parkes 64-m radio telescope (Lorimer et al., 2007), with an additional four bursts discovered in 2013, confirming them as a population (Thornton et al., 2013).

FRBs are sub-divided into two main groups: repeaters and non-repeaters, although there is ongoing debate as to whether or not these are two fundamentally different populations. Non-repeating FRBs are those which have only been detected once, and out of the more than 700¹ FRBs discovered and published to date, most of them fall into this category. Repeating FRBs, on the other hand, are those which have been observed to burst multiple times, and ~ 60 of this type have been published to date (CHIME/FRB Collaboration et al., 2023). The known isotropic energies of FRBs span a range from $\sim 10^{35}$ to 10^{43} erg.

The DMs of known FRBs span from 87.82 pc cm^{-3} for the repeater FRB 20200120E, localised to a globular cluster in M81 (Bhardwaj et al., 2021; Kirsten et al., 2022), to 3338 pc cm^{-3} , for FRB 19920913A (Crawford et al., 2022). The most distant localised FRB is FRB 20220610A, which has a redshift of $z = 1.016 \pm 0.002$ (Ryder et al., 2023). Recently, however, Connor et al. (2024) published the newly discovered FRB 20230521B, which they report as having a redshift of $z = 1.354$. This measurement is tentative for the time being, as it is derived from a single line presumed to correspond to $\text{H}\alpha$. If confirmed, it would exceed the redshift of FRB 20220610A.

The origin of FRBs remains unknown, although numerous models have been suggested. Some of these models propose that FRBs originate from compact objects, and there are numerous ones which predict that at least some FRBs come from magnetars (e.g. Metzger et al. 2017; Beloborodov 2017, 2020; Kumar et al. 2017; Yang & Zhang 2018). Cataclysmic models were at first suggested as potential explanations for FRBs (e.g. Falcke & Rezzolla 2014), but these were ruled out as an explanation for all FRBs once some were found to repeat (Spitler et al. 2016; see Platts et al. 2019 and Zhang 2023 for a comprehensive review of FRB progenitor models). The detection of a bright radio burst (CHIME/FRB Collaboration et al., 2020; Bochenek et al., 2020) from SGR 1935+2154 (Cummings et al., 2014; Lien et al., 2014; Israel et al., 2016), a Galactic magnetar, gave some evidence for the idea that magnetars can cause some FRBs. The radio burst from SGR 1935+2154 is sometimes called the first ‘‘Galactic’’ FRB (FRB 20200428), despite being significantly less luminous than FRBs. There are two main classes of models associated with magnetar progenitors: magnetospheric models, in which the emission comes from close to the surface of the neutron star (Katz, 2016; Kumar et al., 2017; Lu & Kumar, 2018; Wadiasingh & Timokhin, 2019; Kumar & Bošnjak, 2020; Lyutikov & Popov, 2020), and maser shock models, in which the pulse results from maser emission in magnetised shocks (Beloborodov, 2017; Metzger et al., 2019; Beloborodov, 2020).

It remains unclear whether or not non-repeaters and repeaters have different underlying mechanisms, or whether the non-repeaters are simply repeating at much lower rates, and we therefore have not yet observed their repetition. However, there are some differences which have been observed in the burst structures of non-repeaters versus repeater FRBs: repeaters often display what is known as the ‘‘sad trombone effect’’ (Hessels et al., 2019; CHIME/FRB Collaboration et al., 2019; Fonseca et al., 2020; Day et al., 2020), whereby bursts have multiple components that drift downwards in frequency. Non-repeaters, on the other hand, can have bursts with a

¹<https://www.wis-tns.org/>

single component that can be either broad or narrowband, or bursts with multiple components which all peak at the same frequency. Additionally, repeaters tend to be narrower in frequency and wider in time than non-repeaters (Pleunis et al., 2021).

FRBs have not yet been conclusively observed at other wavelengths, and as such, no counterpart of statistical significance has been found, although there have been multiple attempts (e.g. Hardy et al. 2017; Aartsen et al. 2018; Acciari et al. 2018; Callister et al. 2016; Eftekhari et al. 2018; Petroff et al. 2015a; Zhang & Zhang 2017; Trudu et al. 2023; Hiramatsu et al. 2023; Niino et al. 2022; Xing & Yu 2024; Kilpatrick et al. 2021; Kilpatrick et al. 2023; Pearlman et al. 2023; Núñez et al. 2021). A confirmed optical counterpart would help to rule out at least some of the currently suggested models for FRB emission mechanisms. For example, the synchrotron maser model of FRBs predicts a multi-wavelength afterglow, while most magnetospheric models do not. The detection of an optical afterglow would provide evidence in favour of the former model. For the burst associated with SGR 1935+2154, Margalit et al. (2020) interpreted the X-ray counterpart as the X-ray afterglow of the FRB. However, the non-detections of an optical afterglow for FRB 20200428 (e.g. Bailes et al. 2021) greatly constrain the maser shock model (Cooper et al., 2022). In this work, we present our discovery of the to date non-repeating FRB 20230808F, and our search for an optical counterpart, utilising almost simultaneous optical-radio observations.

3.2 Radio Observations and data reduction

3.2.1 MeerTRAP pipeline and FRB 20230808F detection

MeerKAT is a radio telescope array consisting of 64 13.5-m dishes, located in the Karoo in South Africa (Jonas & MeerKAT Team, 2016). MeerKAT’s detection of FRBs is carried out by the Transient User Supplied Equipment (TUSE) instrument of MeerTRAP (Meer(more) TRAnsients and Pulsars; Sanidas et al. 2017; Rajwade et al. 2022; Bezuidenhout et al. 2022; Jankowski et al. 2022), which conducts searches for single pulses concurrently in both coherent and incoherent beams. MeerTRAP is a commensal survey with MeerKAT, and observes simultaneously with all MeerKAT Large Survey Projects and some other projects. The coherent beams (CBs) are formed by a beam-forming instrument called the Filterbanking Beamformer User Supplied Equipment (FBFUSE; Chen et al. 2021; Barr 2017), which coherently combines the signals from the dishes of the telescope array. FBFUSE and TUSE together form the MeerTRAP backend, which can form up to 768 CBs that are highly sensitive and have a total field of view (FoV) of $\sim 0.4 \text{ deg}^2$. This is only a fraction of the primary FoV of MeerKAT, which is $\sim 1 \text{ deg}^2$ at 1284 MHz, although this fraction also depends on the elevation of the source being observed by the telescope (Chen et al., 2021; Rajwade et al., 2022). The incoherent beam (IB) is formed by summing the signals from all of the available antennas, resulting in a less sensitive beam which samples the entire $\sim 1 \text{ deg}^2$ FoV and which usually has around one fifth of the sensitivity of the CBs. AstroAccelerate² (Dimoudi & Armour, 2015; Dimoudi et al., 2018; Adámek & Armour, 2016; Adámek et al., 2017; Adámek & Armour, 2018), a GPU-based single pulse search pipeline, is used to perform a real-time search for dispersed bursts, by incoherently de-dispersing the data in the DM range 0–5118.4 pc cm^{−3} (see Caleb et al. 2020 for further details about the search process).

FRB 20230808F was detected by MeerTRAP at the *L*-band, which is centered on 1284 MHz and has a bandwidth of 856 MHz, on 2023 August 8. The arrival time at the top of the

²<https://github.com/AstroAccelerateOrg/astro-accelerate>

observing band for the FRB was 03:49:15.888 UT and its dispersion measure was found to be $DM = 653.2 \pm 0.4 \text{ pc cm}^{-3}$. The time of arrival at infinite frequency for the FRB was calculated using the arrival time at the top of MeerKAT’s *L*-band (1712 MHz) and taking into account the frequency dispersion in the burst arrival time, due to the ionised interstellar and intergalactic medium³. This resulted in an arrival time at the MeerKAT site of 03:49:14.963 UT on 2023 August 8 at infinite frequency.

3.2.2 Localisation

The detection of FRB 20230808F in a coherent beam and the incoherent beam provides an approximate region of the sky from which the burst originated. The burst passed the detection and machine learning criteria within 45 seconds after the detection, triggering a transient buffer (TB) data dump, whereby high-resolution data around the time of a transient event is captured and stored. The TB data was used to localise the FRB, as well as to obtain the beam-formed data which has a higher spectro-temporal resolution. A detailed description of the MeerTRAP TB system and FRB localisation can be found in Rajwade et al. (2024).

The TB data provides a complex voltage dataset, which contains all of the voltages received by MeerKAT’s antennas that were active at the time of the burst detection. The voltage data contain 300 ms of signal tracing the dispersion curve of the FRB, which is divided into 64 equal sub-bands. The data were imaged using **WSClean** (Offringa et al., 2014), producing a separate image for each frequency sub-band. Following this, we used Python to produce the images which would be used to search for the FRB. This entailed visually inspecting the full 300-ms images so as to flag and then discard the sub-bands which contained radio frequency interference (RFI), before the remaining images were averaged to produce an RFI-free image that was used as a reference image to look for the burst. In addition, images with shorter integration times were produced, in order to determine whether any new source appeared during the central milliseconds, which would be the FRB. In the case of FRB 20230808F, the 300 ms were divided into 31 time intervals, and these smaller timescales were imaged, again averaging the RFI-free frequencies. Difference images were then produced by subtracting the full integration time image from each of the smaller time interval images. A source was found in the difference images for the central time intervals, and, with a location coincident with the CB where it was detected, we concluded that this was the FRB. The full 300 ms were then divided into 489 time intervals in order to enable selection of all images in which the burst was detected, from which we produced an “on” image. Similarly, an “off” image was created containing the same number of time bins, but where the FRB was not present. These on and off images, as well as a new full integration time image, were produced and cleaned with **WSClean**⁴, using the following parameters: the stopping criteria were 100 iterations, or a threshold of 0.01 (arbitrary units). We applied a **Cotton-Schwab** (Schwab, 1984) cleaning with major iteration gain of 0.8, and auto-masking threshold of $\sigma = 3$. We used a Briggs weighting with a robustness parameter of -0.3 with a weight rank filter of 3. Lastly, we applied a W-gridding mode. The final images were centred at the phase centre of the observation, they have a pixel size of 1 arcsec^2 , and a size of 4096×4096 pixels. The clean on and off images, zoomed at the location of the FRB, are shown in Figure 3.1.

Following this, astrometry was performed using the method described in Driessen et al. (2023), by running the Python Blob Detector and Source Finder (**pyBDSF**; Mohan & Rafferty 2015)

³The dispersive time delay is calculated using the dispersion constant $D = 4.1488 \times 10^3 \text{ MHz}^2 \text{ pc}^{-1} \text{ cm}^3 \text{ s}$.

⁴WSClean is an imaging algorithm for radio data that uses w-stacking to correct for w-term effects after the FFT. Further details can be found at: <https://ws-clean.readthedocs.io/en/latest/>

FRB 20230808F

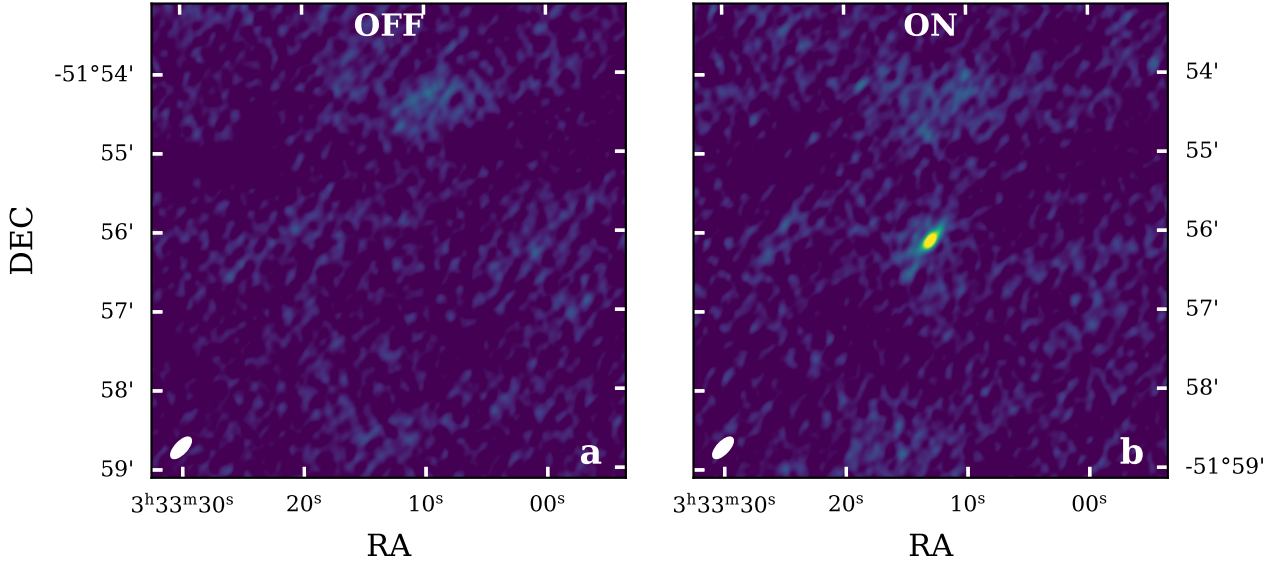


Figure 3.1: “Off” and “on” cleaned images showing the burst of FRB 20230808F. Each image has a total exposure time of approximately 14.7 ms.

algorithm to identify the positions of the sources in the images. The astrometric transformation was obtained by searching other radio catalogues with known sources in the FoV, which were used as references. Although we prioritise using catalogues with a positional accuracy $< 0.5''$, the FoV of FRB 20230808F is not covered by any such catalogues containing sufficient sources to perform the astrometric correction ($\gtrsim 5$). While the Rapid ASKAP Continuum Survey (RACS-mid; Duchesne et al. 2023) contains sufficient sources within the FRB FoV, its sources have systematic positional uncertainties of $1\text{--}2''$. Thus, as described in Rajwade et al. (2024), we use the Radio Fundamental Catalog (RFC)⁵ to correct the RACS-mid source positions. The RFC has source positions with milli-arcsecond accuracy, and while it does not contain enough sources to perform the astrometric correction of the FRB FoV, it is enough to correct the RACS-mid source positions within a 5 degree radius. We then used the RACS-mid corrected source positions to correct the MeerKAT images. The astrometric correction was performed with the Python package **Astroalign** (Beroiz et al., 2020), and only sources classified as point-like were used. The transformation was applied to the on, off, and full integration time images, and the corrected FRB coordinates were then obtained from the transformed on image. The position errors for the FRB were obtained by summing in quadrature the position error from **pyBDSF**, and the astrometric error from the two transformations, which is defined as the mean angular separation between the sources in the reference catalogue and the corrected coordinates of sources in the target catalogue. In our case, the reference and target catalogues for the first astrometric correction were RFC and RACS, respectively, and for the second correction they were RACS and MeerTRAP. FRB 20230808F was localised to a position of $\text{RA (J2000)} = 03^{\text{h}}33^{\text{m}}12^{\text{s}}.99 \pm 0^{\text{s}}.03$ and $\text{Dec (J2000)} = -51^{\circ}56'07''.02 \pm 0''.50$.

3.2.3 Burst structure and timing analysis

Using the localised FRB coordinates, the TB data were beamformed at the correct FRB position, resulting in a boost in the signal-to-noise ratio (S/N; see Rajwade et al. 2024 for further

⁵RFC: <http://astrogeo.org/rfc/>

details of this process). The TB data had a higher spectro-temporal resolution, and were coherently de-dispersed at the DM of the burst, eliminating intra-channel smearing. The beamformed data were used to resolve the FRB components, along with the scattering timescale. To fit the temporal structure of the FRB, the frequency range where the burst emission was most visible - primarily at the upper end of the observing bandwidth - was selected to enhance the S/N of the pulse profile. This involved averaging the dynamic spectrum in time, fitting it with a Gaussian function, and then selecting frequencies within the Full Width at Tenth Maximum (FWTM) of the fitted Gaussian. For FRB 20230808F, this range spanned from 1415.25 MHz to 1738.23 MHz. The upper frequency limit is above the maximum of MeerKAT's *L*-band, so all channels above 1415.25 MHz up to 1712 MHz were included. In order to fit the pulse to a multi-component model with scattering, a semi-automated fitting routine was created to select the locations of the components, fit multi-component scattered Gaussians, and then find the optimal number of components and scattering timescale. The fitting routine models the pulse profile of an FRB using a multi-component scattered Gaussian model. This is done by first smoothing the pulse profile with a Blackman window of length 15 and identifying local maxima within the smoothed pulse profile. A range for the number of components (minimum and maximum) is provided as input, and the largest peaks in the smoothed profile are used as initial guesses for the component locations. The profile is then fitted iteratively using `lmfit.Minimizer` and custom functions that convolve multiple Gaussians with a one-sided exponential decay to add scattering. The fitting process minimizes the difference between the model and the data, adding components iteratively by smoothing residuals and identifying additional peaks, until the maximum component number is reached. The optimal number of components is then chosen based on the lowest Bayesian Information Criterion (BIC), yielding the number of components, scattering timescale, and the arrival time, amplitude, and width of each component. This resulted in an optimal number of components of 6, along with the time of arrival (ToA) of each component, and a scattering timescale $\tau_s = 3.1 \pm 0.1$ ms. The latter is measured at 1563.6 MHz, which is the central frequency of the burst bandwidth. The locations of the 6 burst components are shown in Figure 3.2.

The method described in Pastor-Marazuela et al. (2023) was used to test for periodicity in the burst structure and to obtain the component arrangement. The ToAs as a function of component number were fitted to a linear function of the form:

$$t_i = \bar{d}n_i + T_0, \quad (3.1)$$

where t_i is the i -th arrival time, $\bar{d}$ is the mean spacing between the sub-components of the burst, n_i is the i -th component number, and T_0 is the first ToA. The fitting was conducted using the Python package `lmfit`⁶ (Newville et al., 2024). A least squares minimisation technique, weighted by the inverse of the ToA errors, was used to determine the mean sub-component separation P_{sc} , equivalent to $\bar{d}$, and the goodness of fit was assessed using the reduced chi squared statistic, χ_r^2 . This yielded $P_{sc} = 1.55 \pm 0.03$ ms.

To test the significance of the periodicity, 10^5 bursts with six sub-components and random separations were simulated and the same linear fit described by Eq 3.1 was performed, with the resulting distribution of χ_r^2 values compared to the χ_r^2 for the FRB. The sub-burst separations were simulated using two different distributions, namely a rectangular and a Poissonian distribution, and using different exclusion parameters. The exclusion parameter η is the minimal separation fraction that we consider would be resolved by the fitting routine. Using rectangular simulations, the periodicity significance was equal to 2.22σ , while for the Poissonian distri-

⁶<https://pypi.org/project/lmfit/>

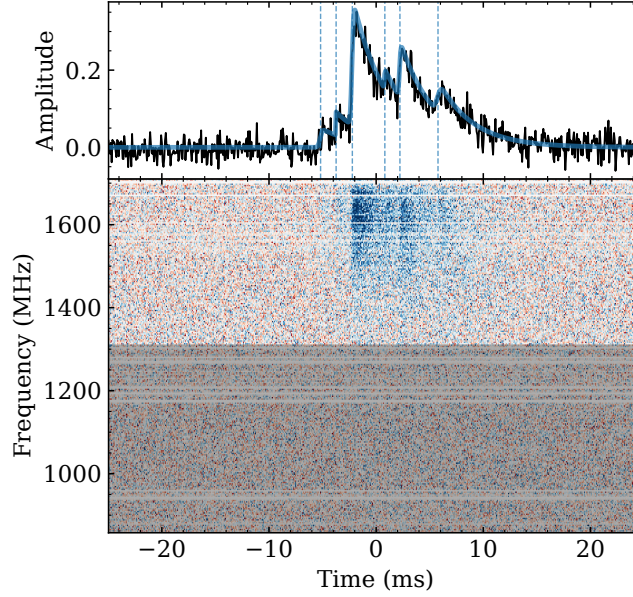


Figure 3.2: Dynamic spectrum and burst profile of FRB 20230808F. The black solid line in the top panel shows the averaged pulse profile, the solid blue line shows the fit to a multi-component scattered Gaussian, and the dashed blue lines indicate the positions of the six burst components. The dynamic spectrum is shown in the bottom panel.

bution, the significance was 2.11σ . In both cases, therefore, we do not find that the burst is significantly periodic.

3.2.4 Polarisation and rotation measure

The TB data provide full Stokes I, Q, U and V information, which was used to obtain the rotation measure and intrinsic polarisation properties of the burst. The Faraday rotation measure (RM) for FRB 20230808F was measured using the `RM-Tools` algorithm (Purcell et al., 2020), which applies the RM synthesis technique (Burn, 1966; Brentjens & de Bruyn, 2005). This yielded a $\text{RM} = 169.4 \pm 0.2 \text{ rad m}^{-2}$. We then de-rotated the Stokes Q/U data at the measured RM, which removed any variations with frequency and enabled us to study the intrinsic emission. The average linear polarisation factor, L/I, was found to be 106.6 ± 14.8 per cent, while the average circular polarisation factor, V/I, was found to be 10.4 ± 7.8 per cent. These values are consistent with 100 per cent linear and 0 per cent circular polarisation fractions, which is what is commonly observed in repeating and some one-off FRBs (e.g. Cho et al. 2020; Day et al. 2020; Luo et al. 2020; Michilli et al. 2018; Pandhi et al. 2024). The polarisation position angle (PPA) is given by:

$$\psi(t) = \frac{1}{2} \tan^{-1} \frac{U_{\text{derot}}(t)}{Q_{\text{derot}}(t)}. \quad (3.2)$$

The PPA is shown in the top panel of Figure 3.3, and we found that it appears to step from 60° to 80° over the duration of the burst, which is consistent with behaviour seen in multiple pulsars and magnetars, and other FRBs (e.g. Cho et al. 2020; Luo et al. 2020).

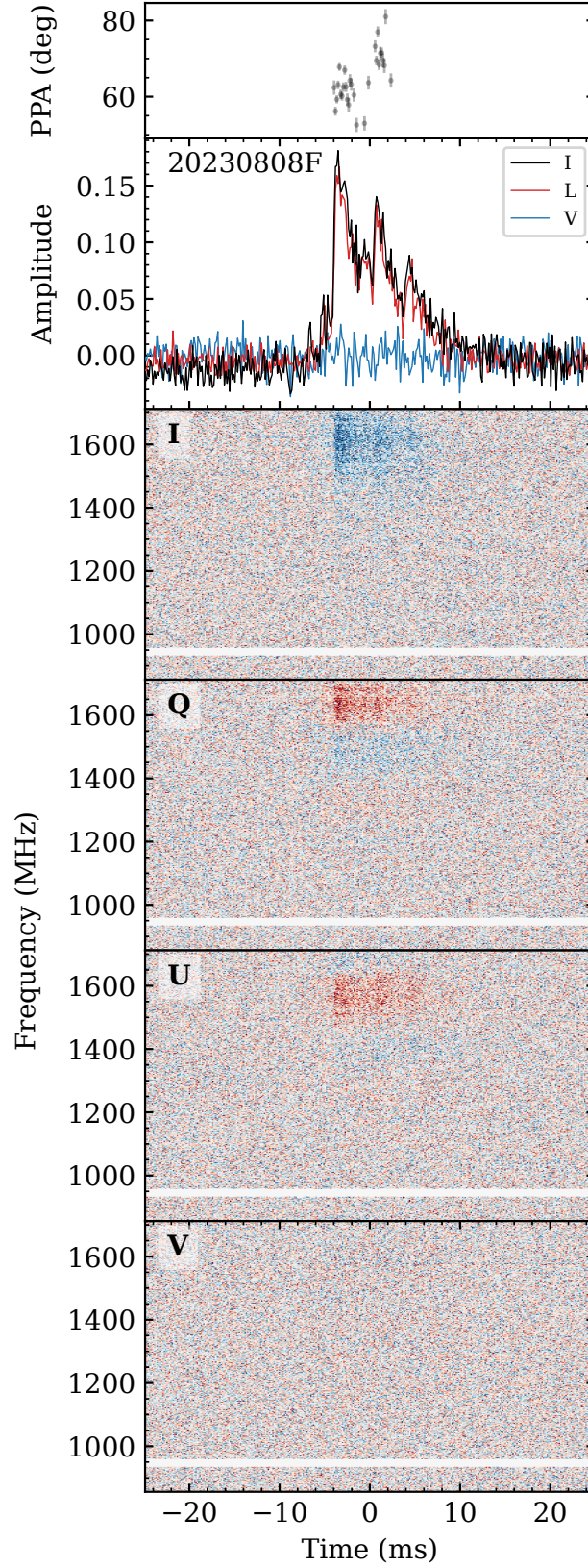


Figure 3.3: Stokes I, Q, U and V data for FRB 20230808F are shown in the four bottom panels, prior to the de-rotation of Stokes Q/U. The top two panels show the PPA and pulse profile, respectively, both after de-rotating Q/U, and a scattering tail is visible in the pulse profile. The blue in the Stokes panels indicates positive intensity values, while red is associated with negative values. The dynamic spectrum has a time resolution of $36.62 \mu\text{s}$ and a frequency resolution of 3.34 MHz .

3.3 Host galaxy and optical counterpart search

3.3.1 Identification of host galaxy

After localising the FRB, we searched at the coordinates of the burst in the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2016) Legacy Survey’s tenth data release (hereafter DESI DR10), and it was apparent that there were two potential host galaxies, although the burst location appeared closer to one of the two. From visual inspection, the two galaxies appeared to possibly be interacting, as can be seen, along with the FRB coordinates, in Figure 3.6. The coordinates of the two galaxies are RA (J2000) = $03^{\text{h}}33^{\text{m}}12^{\text{s}}.70$, Dec (J2000) = $-51^{\circ}56'06''.72$ for the northernmost galaxy (hereafter north galaxy) and RA (J2000) = $03^{\text{h}}33^{\text{m}}12^{\text{s}}.83$, Dec (J2000) = $-51^{\circ}56'09''.27$ for the southernmost galaxy (hereafter south galaxy).

We run the Probabilistic Association of Transients to their Hosts (PATH) algorithm (Aggarwal et al., 2021) for a sample of galaxies from DESI DR10 within a FoV of 30 arcseconds around the FRB position. PATH is a Bayesian algorithm that provides posterior probabilities ($P(O_i|x)$) for host associations based on observables and priors that depend only on photometry and astrometry (including the FRB position uncertainty). We used photometry in the r -band with an exponential profile prior centred in each candidate galaxy with a characteristic scale given by their half-light radii (r_e) up to a maximum of $10 \times r_e$. We also used a prior on the true host not being included in the catalog (i.e. “unseen”) of $P(U) = 0.05$. The rest of the parameters were set as default in the PATH repository.⁷ We obtained $P(O_i|x) = 0.59$ and $P(O_i|x) = 0.37$, for the north and south galaxy respectively. Changing the characteristic scale of the prior exponential profile to $r_e/2$ as suggested by Shannon et al. (2024) does not significantly change the posteriors. This analysis provides support to the association of the FRB with either of the two closest identified galaxies, with the sum of these posterior probabilities being larger than 0.9. We note that, while PATH assigns a higher association probability to the north galaxy, the algorithm does not take into account the ellipticity and orientation of the host galaxy candidates. From the optical image, shown in Figure 3.6, the FRB localisation seems to fall within the extension of the south galaxy.

Zou et al. (2022) calculated the photometric redshifts for around 293 million galaxies with $i < 24$ in DES DR2, including the two potential host galaxies. The photometric redshift for the north galaxy from Zou et al. (2022) is $z_{\text{phot}} = 0.42 \pm 0.06$, while that of the south galaxy is $z_{\text{phot}} = 0.53 \pm 0.07$. These two redshifts agree within uncertainties, implying that the galaxies may be a close, potentially interacting pair. The DESI DR10 magnitudes for the galaxies are presented in Table 3.2, and various properties of the galaxies resulting from the SED fitting are shown in Table 3.3. The star formation rates (SFRs) obtained for both galaxies are negative, which likely means that the true SFR is low, consistent with zero. We also note the comment made by the authors, which cautions the reader against using the star formation rate and stellar age parameters from their catalogue.

3.3.2 MeerLICHT optical counterpart search

MeerLICHT, situated at the South African Astronomical Observatory site near Sutherland in South Africa, is a fully robotic, wide-field optical telescope. The telescope has a 0.65 m primary mirror and a 2.7 deg^2 field of view, and was built as a prototype for the BlackGEM array in Chile (Groot et al., 2024). MeerLICHT has a filter wheel which consists of the Sloan Digital

⁷<https://github.com/FRBs/astropath>

Sky Survey (SDSS; York et al. 2000) u , g , r , i and z filters, and a wider q band which spans the range of 440–720 nm (Groot et al., 2024). MeerLICHT has a declination upper limit of $+30^\circ$, and pointing limits of $> 20^\circ$ above the horizon in elevation (Groot et al., 2024) and hour angle limit greater than -3 hours and less than 4.5 hours. When the aforementioned conditions are met, MeerLICHT co-observes with MeerKAT, and if syncing cannot be established for one or more reasons, the telescope either follows its backup program of observing regions of Local Universe mass over-densities, follows up other high priority targets, or it builds up reference images for its survey of the southern sky.

When MeerLICHT is synced with MeerKAT, it observes in one-minute exposures, and every second image is a q -band exposure in the sequence $q, g, q, i, q, u, q, r, q, z, q$. When not synced with MeerKAT, MeerLICHT observes in the filter sequence q, u, i, q, u, i , etc., also with an integration time of one minute. Regardless of whether or not it is linked with MeerKAT, there are approximately 25 seconds of overhead time in between each MeerLICHT exposure, which allows for filter change, re-pointing of the telescope, and image readout.

MeerLICHT images are reduced using two pieces of Python software: BlackBOX (Vreeswijk & Paterson, 2021a) and ZOGY⁸ (Vreeswijk & Paterson, 2021b; Zackay et al., 2016). Routine CCD reduction procedures are carried out by BlackBOX on the raw science images, and then ZOGY performs source identification, photometry, astrometry, and finds transient candidates. The method for finding transient candidates is based on the image subtraction routine developed by Zackay et al. (2016). The reduced images are available on *ilifu*⁹, which is a cloud facility operated by the Inter-University Institute for Data Intensive Astronomy (IDIA) and hosted at the University of Cape Town.

One of MeerLICHT’s primary science goals is to try and simultaneously observe FRBs, along with MeerKAT/MeerTRAP. In the early morning on 2023 August 8, MeerLICHT synced with MeerKAT while the latter was observing the MHONGOOSE (SCI-20180516-EB-01) field where the FRB occurred, which corresponds to the MeerLICHT fixed sky-grid field 16074. MeerLICHT commenced observations of the field at around 02:05 UT. The arrival time of FRB 20230808F occurred while the two telescopes were linked, although it was within MeerLICHT’s overhead time, in between a u -band exposure and a q -band exposure. The q -band exposure started approximately 3.4 seconds after the arrival time of the FRB, at 03:49:18.32 UT.

The MeerLICHT exposures taken of field 16074 were accessed using *ilifu*, where we first visually inspected the images taken immediately before and after the arrival of the FRB. No obvious optical emission at the location of the FRB was seen. We created co-adds around the time of the FRB as well, using the co-adding package for MeerLICHT, *buildref.py*¹⁰. The following co-adds were made: a co-add per filter of all MeerLICHT images of field 16074 until 5 days before the FRB (hereafter referred to as the deep co-add), a co-add per filter of all exposures of the field in the 20 minutes before the FRB, one per filter of all exposures in the 20 minutes after the FRB, and then 15 minutes before and after, 5 minutes before and after, and 1 minute before and after the burst arrival time. As the MeerLICHT exposures are 60 seconds in length, the “1-minute” co-adds each had one image only. We then ran ZOGY to perform image subtraction, using the deep co-add for each filter as a reference image, and subtracting these from all of the other co-adds. After performing the image subtraction, we ran

⁸<https://github.com/pmvreeswijk/ZOGY/blob/main/zogy.py>

⁹<https://www.ilifu.ac.za/>

¹⁰<https://github.com/pmvreeswijk/BlackBOX/blob/main/buildref.py>

Table 3.1: Observation parameters for the four SALT observations.

Date	No. exposures	Length of each exposure (s)
2023 November 3	2	1200
2023 November 5	2	1200
2023 December 11	2	1800
2023 December 16	2	1700

the forced photometry package for MeerLICHT, `force_phot.py`¹¹ (Vreeswijk et al., in prep), on the resulting images in order to extract flux measurements at the coordinates of the FRB at various times around the arrival of the burst. Photometric and astrometric calibrations for MeerLICHT data are carried out using a catalogue of Gaia DR2 (Brown et al., 2018) stars.

MeerLICHT re-observed field 16074 on the night of 2023 September 6. We chose a 300 s integration time, as opposed to the usual 60 seconds, so that we could obtain deeper exposures of the field. These images – five each in the u -, q -, i - and z - bands and four in the g -band – were then also co-added and we ran image subtraction and forced photometry on the resulting co-added images. In addition, field 16074 was given high priority status in MeerLICHT’s scheduler, so that it would be observed more frequently as part of MeerLICHT’s backup program whenever it was not synced with MeerKAT. As a result of this, the field was observed regularly over the subsequent months, and we created a co-add per filter of all of the MeerLICHT exposures of the field in the 3 months post-FRB, as well as “per night” co-adds for all of the individual nights post-FRB on which the field was observed.

We corrected for Milky Way (MW) dust extinction for all of our photometry results. We found the colour excess in the MW in the direction of FRB 20230808F, $E(B - V)_{\text{MW}}$, in each of MeerLICHT’s filters, based on the colour excess map by Schlafly & Finkbeiner (2011)¹². We assumed the Fitzpatrick (1999) reddening law with $R_V = 3.1$, where R_V is the total-to-selective extinction ratio. The MW-dust-extinction-corrected photometry results can be seen in Table 3.5, and are also shown in Figures 3.4a and 3.4b.

Our deep co-add, shown in Figure 3.5, shows a faint underlying extended source at the coordinates of the FRB. This is consistent with the north and south galaxies identified in Section 3.3.1.

3.3.3 SALT spectra

We observed the two galaxies using the Robert Stobie Spectrograph (RSS; Burgh et al. 2003) on the 11 m Southern African Large Telescope (SALT; Buckley et al. 2006), to determine their spectroscopic redshifts.

We observed the field of FRB 20230808F on four separate occasions, and the summary of the observations is shown in Table 3.1.

For our two observations in November, the SALT Imaging Camera (SALTICAM), SALT’s sensitive acquisition camera, had been removed for repairs, and a backup CCD camera, BCAM, was in its place. BCAM is a basic Apogee CCD camera, and is much less sensitive than SALTICAM. The position angle (PA) of the slit was set to -40° , and we used a slit width of

¹¹https://github.com/pmvreeswijk/ZOGY/blob/main/force_phot.py

¹²<https://www.ipac.caltech.edu/doi/ned/10.26132/NED5>

1.5". We had initially requested a slit position angle of -25° , to pass through both galaxy nuclei as well as two faint alignment stars, but the alignment stars were too faint for BCAM, and as such, we had to adjust the PA to allow for a much brighter alignment star. SALT took these two observations using the PG0700 grating, which covers a wavelength range of 320–900 nm. The obtained spectra were faint in the continuum, but with a clear emission line at 5021 Å.

For the observations on 2023 December 11, the same spectral setup as before was used, but this time with SALTICAM, and therefore the originally desired slit PA of -25° was used. The final observations on the 2023 December 16 again used SALTICAM, but this time with a redder spectral set-up, using a slit width of 1.25" and the PG0900 grating, which also spans 320–900 nm but has higher usable angles, increasing the spectral resolution and efficiency at longer wavelengths. A possible emission line was observed at 8840 Å, although the spectrum was heavily impacted by skyline residuals. The slit orientations for all of the SALT observations are shown in Figure 3.6.

The emission line at 5021 Å was determined to be the [O II] doublet, which corresponds to a redshift of $z_{\text{spec}} \sim 0.347$, and there are confirming H β and [O III] lines at the same redshift at 6548 Å and 6743 Å, respectively. All three lines are clearly visible in the exposures from 2023 November 5 and 2023 December 11, while the spectrum from 2023 November 3 shows the [O II] and H β emission lines. The emission line at 8840 Å from 2023 December 16 matches the expected position of H α at the calculated redshift. The spectra from all four nights are shown, with their identified emission lines labeled in the rest frame, in Figures 3.8a, 3.8b, 3.8c and 3.8d. The emission in all of the spectra was determined to be from the north galaxy by comparing the distances between the traces in the 2D spectra and the distances between the reference stars and the galaxies in the various observation set-ups. An example of this is shown in Figure 3.7.

The calculated spectroscopic redshift of $z_{\text{spec}} = 0.3472 \pm 0.0002$ is in agreement with the photometric redshift of the north galaxy within 1.13σ . Using the spectroscopic redshift, we calculated the luminosity distance, D_L , as 1903.4 Mpc, assuming cosmological parameters from the Planck Collaboration et al. (2020).

3.4 FRB 20230808F characteristics

3.4.1 Radio flux and fluence

The peak flux density for FRB 20230808F was calculated as described in Jankowski et al. (2023), using a modified version of the single-pulse radiometer equation (Dewey et al., 1985):

$$S_{\text{peak}}(S/N, W_{\text{eq}}, \vec{a}) = S/N \beta \eta_b \frac{T_{\text{sys}} + T_{\text{sky}}}{G \sqrt{b_{\text{eff}} N_p W_{\text{eq}}}} a_{\text{CB}}^{-1} a_{\text{IB}}^{-1}, \quad (3.3)$$

where S_{peak} is the peak flux density, $\vec{a}$ is the parameter vector, β is the digitisation loss factor, which is 1.0 for 8-bit digitisation (Kouwenhoven & Voûte, 2001), η_b is the beam-forming efficiency, taken to be ~ 1 (Chen et al., 2021), G is the telescope forward gain, b_{eff} is the effective bandwidth, $N_p = 2$ is the number of polarisations summed, W_{eq} is the observed equivalent boxcar pulse width, $T_{\text{sys}} = 19$ K and T_{sky} are the system and sky temperatures, and $a_{\text{CB}} = 0.9$ and $a_{\text{IB}} = 0.8$ are the attenuation factors of the detection CB and the IB. The radio flux density was thus found to be $S_{\text{peak}} = (157 \pm 14)$ mJy, calculated from the filterbank data where the FRB was detected. The fluence F_{radio} was then calculated from $F_{\text{radio}} = S_{\text{peak}} W_{\text{eq}}$, yielding $F_{\text{radio}} = (1.72 \pm 0.01)$ Jy ms.

Using the peak flux density and fluence, we computed the isotropic luminosity, L_p , and energy, E , of the burst, as described in Zhang (2018b), using:

$$L_p \simeq 4\pi D_L^2 S_{\nu,p} \nu_c = (10^{42} \text{ erg s}^{-1}) 4\pi \left(\frac{D_L}{10^{28} \text{ cm}} \right)^2 \frac{S_{\nu,p}}{\text{Jy}} \frac{\nu_c}{\text{GHz}}, \quad (3.4)$$

$$E \simeq \frac{4\pi D_L^2}{1+z} F_\nu \nu_c = (10^{39} \text{ erg}) \frac{4\pi}{1+z} \left(\frac{D_L}{10^{28} \text{ cm}} \right)^2 \frac{F_\nu}{\text{Jy} \cdot \text{ms}} \frac{\nu_c}{\text{GHz}}, \quad (3.5)$$

where $S_{\nu,p}$ is the specific peak flux density, F_ν is the specific fluence, ν_c is the central frequency of the observing band, and D_L is the luminosity distance, obtained in Section 3.3.3. Using the values pertaining to FRB 20230808F, we obtained $L_p = 8.7 \times 10^{41} \text{ erg s}^{-1}$ and $E = 7.1 \times 10^{39} \text{ erg}$. However, we note that using the central frequency when calculating the luminosity and energy would imply a flat burst spectrum, and as such, following the prescription of Aggarwal (2021), we also used the burst bandwidth, instead of the central observing frequency, to calculate the energy and luminosity of FRB 20230808. Doing so yielded $L_p = 2.0 \times 10^{41} \text{ erg s}^{-1}$ and $E = 1.6 \times 10^{39} \text{ erg}$.

3.4.2 Host galaxy contribution to propagation properties

We used the FRBs¹³ library (Prochaska & Zheng, 2019; Prochaska et al., 2023) to calculate the expected DM contributions, rotation measure, and redshift for FRB 20230808.

The total observed FRB DM is the sum of the DM contributions from the MW, MW halo, the intergalactic medium (IGM), and the host galaxy, and can thus be expressed as

$$\text{DM} = \text{DM}_{\text{MW}} + \text{DM}_{\text{halo}} + \text{DM}_{\text{IGM}} + \frac{\text{DM}_{\text{host}}}{1+z}. \quad (3.6)$$

The expected MW DM contribution in the direction of the FRB, according to the YMW16 model (Yao et al., 2017), is $\sim 35 \text{ pc cm}^{-3}$, with an expected $\tau_s \sim 4.8 \times 10^{-8} \text{ s}$ in the L -band. According to the NE2001 model (Cordes & Lazio, 2003), the MW DM contribution is $\sim 27 \text{ pc cm}^{-3}$, with an expected $\tau_s \sim 4.3 \times 10^{-8} \text{ s}$ in the L -band. Taking the average between the YMW16 and NE2001 DM_{MW} values, we obtain $\text{DM}_{\text{MW}} \sim 31 \text{ pc cm}^{-3}$. We used the model from Yamasaki & Totani (2020) to estimate the DM contribution from the MW halo (DM_{halo}), which was found to be $\sim 33 \text{ pc cm}^{-3}$.

The redshift upper limit was computed using the cosmological parameters from the Planck Collaboration et al. (2020). By applying the Macquart relation (Macquart et al., 2020), we adjusted the value of DM_{host} until the predicted redshift matched the spectroscopic redshift of 0.3472 ± 0.0002 , thus obtaining $\text{DM}_{\text{host}} \sim 420 \text{ pc cm}^{-3}$ in the host galaxy reference frame. Subtracting all of the calculated DM contributions from the total observed DM of $\sim 653 \text{ pc cm}^{-3}$, we obtain $\text{DM}_{\text{IGM}} \sim 277 \text{ pc cm}^{-3}$.

We calculated the MW contribution to the RM using the Faraday sky model from Hutschenreuter et al. (2022). The expected MW contribution to the RM in the direction of the FRB is $\sim 18 \text{ rad m}^{-2}$, while that at the host was found to be $\sim 274 \text{ rad m}^{-2}$.

The expected MW scattering timescales are orders of magnitude smaller than the actual FRB scattering timescale of $\tau_s = (3.10 \pm 0.13) \text{ ms}$. The expected scattering timescales and the calculated values for the DM and RM contributions, indicate that there are significant extragalactic

¹³<https://github.com/FRBs/FRB>

Table 3.2: DESI DR10 magnitudes for the two potential identified host galaxies.

Filter	North galaxy	South Galaxy
<i>g</i>	22.3	22.9
<i>r</i>	21.4	21.6
<i>i</i>	21.0	21.1
<i>z</i>	20.6	20.7

Table 3.3: Estimated age, log stellar mass, and star formation rate for each of the potential host galaxies, obtained from the SED fitting performed by Zou et al. (2022). The upper SFR refers to the upper limit of the star formation rate with a 68 per cent confidence level.

Property	North galaxy	South galaxy
Age (yr)	8×10^9	4×10^9
Mass (dex)	10.26	10.33
Best SFR ($M_{\odot} \text{ yr}^{-1}$)	-0.1	-0.1
Upper SFR ($M_{\odot} \text{ yr}^{-1}$)	0.2	0.0

contributions to all of these propagation properties from either the FRB environment, the host galaxy, or a foreground galaxy. However, disentangling the individual contributions from each of these components is challenging.

3.4.3 Optical flux limits

Table 3.5 summarizes the upper limits for optical emission in the seconds, minutes and months following the FRB arrival time. For many of the co-adds we created, the S/N was lower than 3, and for these cases we used the limiting magnitude at a significance level of 3σ at the coordinates of the FRB instead of the magnitude value and associated error. As such, in Table 3.5, the limits which include uncertainties are those where the S/N was greater than 3, and hence where the actual magnitude value was used. Figures 3.4a and 3.4b show plots of the upper limits derived from the photometry. Points on these plots which have vertical errorbars are those for which actual magnitude measurements were used, whereas points without represent limiting magnitudes. The horizontal “error bars” represent the timespans over which the images used to create the co-adds were obtained. Although we have used both limiting magnitudes and actual magnitudes to obtain upper limits on optical emission for FRB 20230808F, it should be noted that an upper limit taken from a limiting magnitude is a feature of the observation, whereas upper limits taken from actual magnitudes relate to the source itself.

No optical counterpart was found for FRB 20230808F in our almost simultaneous or follow-up observations. In the time just after the burst, we were able to set an optical upper flux limit in the *q*-band of $f_{\text{AB},q} < 11.7 \mu\text{Jy}$, while for our *u*-band observation which ended approximately 24.7 seconds before the FRB arrival time, we obtained an upper limit of $f_{\text{AB},u} < 46.9 \mu\text{Jy}$. We also obtained upper limits on various nights over the course of the 3 months after the FRB.

3.4.4 Fluence ratio limit and optical luminosity limit

The flux upper limit in the *q*-band of $f_{\text{AB},q} < 11.7 \mu\text{Jy}$ corresponds to a fluence of $F_{\text{opt}} = 0.039 \text{ Jy ms}$ if we conservatively assume that the duration of a possible optical burst $t_{\text{opt}} \approx \Delta t$, where $\Delta t \approx 3.4 \text{ s}$ is the time delay between the FRB and the start of our optical observation. Choosing this timescale allows us to consider the shortest possible optical burst that could still

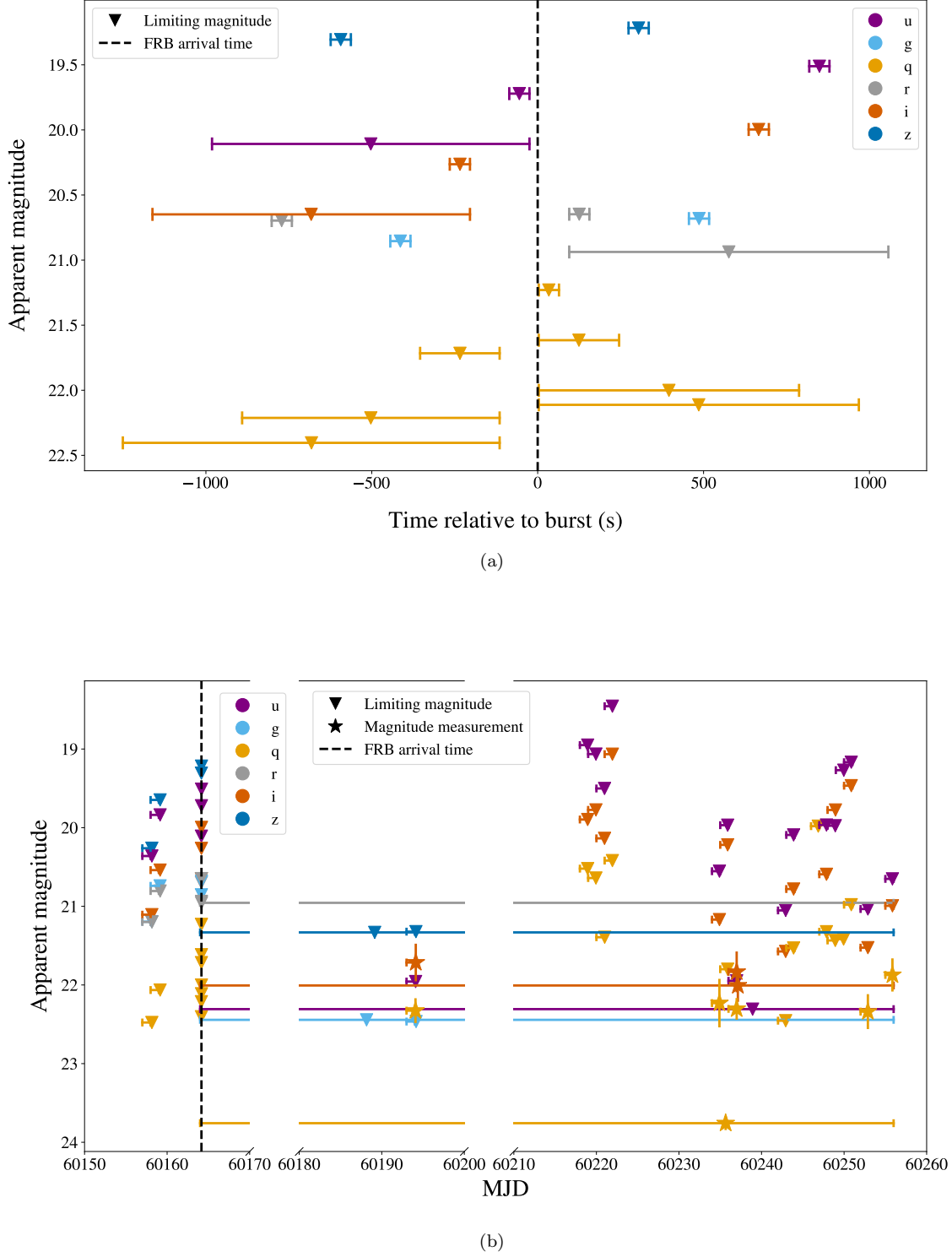


Figure 3.4: Forced photometry results for FRB 20230808F. In both plots, each colour represents a different MeerLICHT filter, upside down triangles indicate limiting magnitudes, and stars represent actual magnitude measurements where the S/N was greater than 3. The dashed black line in each plot indicates the MJD at which FRB 20230808F took place. The forced photometry results from the night of the FRB, with apparent magnitude plotted against modified Julian date (MJD), and horizontal errorbars representing the time-span over which a co-add was made, are shown in (a). The forced photometry results at the FRB coordinates, for all of the MeerLICHT images of field 16074, but excluding the deep co-add, are shown in (b). The deep co-add is excluded because it was used as the reference image for image subtraction.

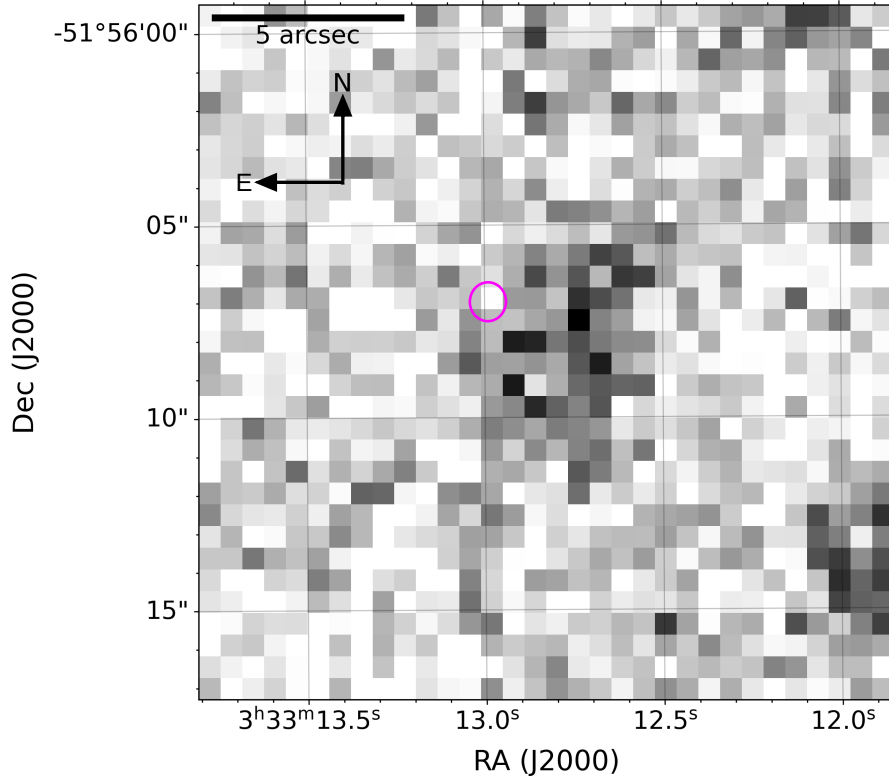


Figure 3.5: Co-add image produced using all MeerLICHT data of the field of FRB 20230808F up until shortly before the burst. The magenta ellipse indicates the position of the FRB, and the underlying galaxies are visible but unresolved in this image. The resolved galaxies are shown in Figure 3.6.

be detectable under our observing conditions, and this is the same timescale used by Hiramatsu et al. (2023) for calculating fluence limits where there was a delay between the burst arrival time and the start of an optical exposure. We thus obtain a fluence ratio $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.023$ on a timescale of ~ 3.4 s. We also evaluated the fluence limit on a longer timescale of the delay time plus the full integration time. In this case, the fluence limit is $F_{\text{opt}} = 0.74$ Jy ms, and the fluence ratio is then $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.43$ on a timescale of ~ 63.4 s.

For our first observation after the FRB, we were able to obtain a MeerLICHT q -band luminosity limit of $\nu L_{\nu} \sim 1.3 \times 10^{43}$ erg s $^{-1}$ with a 60 s exposure starting ~ 3.4 s after the arrival of the FRB. This corresponds to an optical energy limit $E_{\text{opt}} \sim 7.9 \times 10^{44}$ erg, which yields an energy ratio $E_{\text{opt}}/E_{\text{radio}} \lesssim 4.8 \times 10^5$ if we use the radio burst energy calculated using the burst bandwidth.

3.5 FRB 20230808F in context

3.5.1 Comparison to previous optical limits

Hardy et al. (2017) simultaneously observed the repeater FRB 20121102, which has a redshift of $z = 0.19$ (Tendulkar et al., 2017), with the 100-m Effelsberg Radio Telescope and ULTRASPEC, which is mounted on the 2.4-m Thai National Telescope (Dhillon et al., 2014). They detected 13 bursts in the radio and stacked the optical data around the arrival time of each of the bursts. They obtained an optical fluence limit of 0.17 Jy ms on a timescale of 141.4 ms, corrected for MW dust extinction, which corresponds to an optical-to-radio fluence ratio limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.28$.

The MAGIC Collaboration et al. (2018) conducted simultaneous radio, optical, and very-high-energy (VHE) gamma-ray observations of FRB 20121102, making use of the Arecibo radio

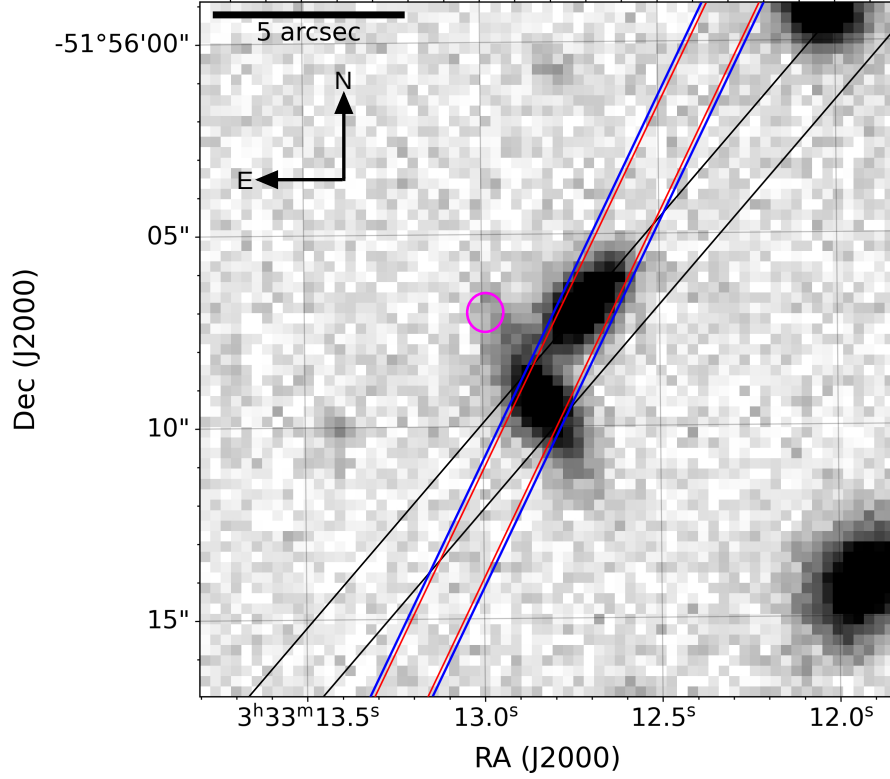


Figure 3.6: Two host galaxy candidates can be seen in the *i*-band image above, taken from the Dark Energy Survey's (DES; The Dark Energy Survey Collaboration 2005) second public data release (hereafter DR2; Abbott et al. 2021). The magenta ellipse indicates the position with uncertainties of FRB 20230808F. The black parallel lines indicate the slit position for the November SALT observations, and the blue and red parallel lines show the slit for the 2023 December 11 and 2023 December 16 observations, respectively.

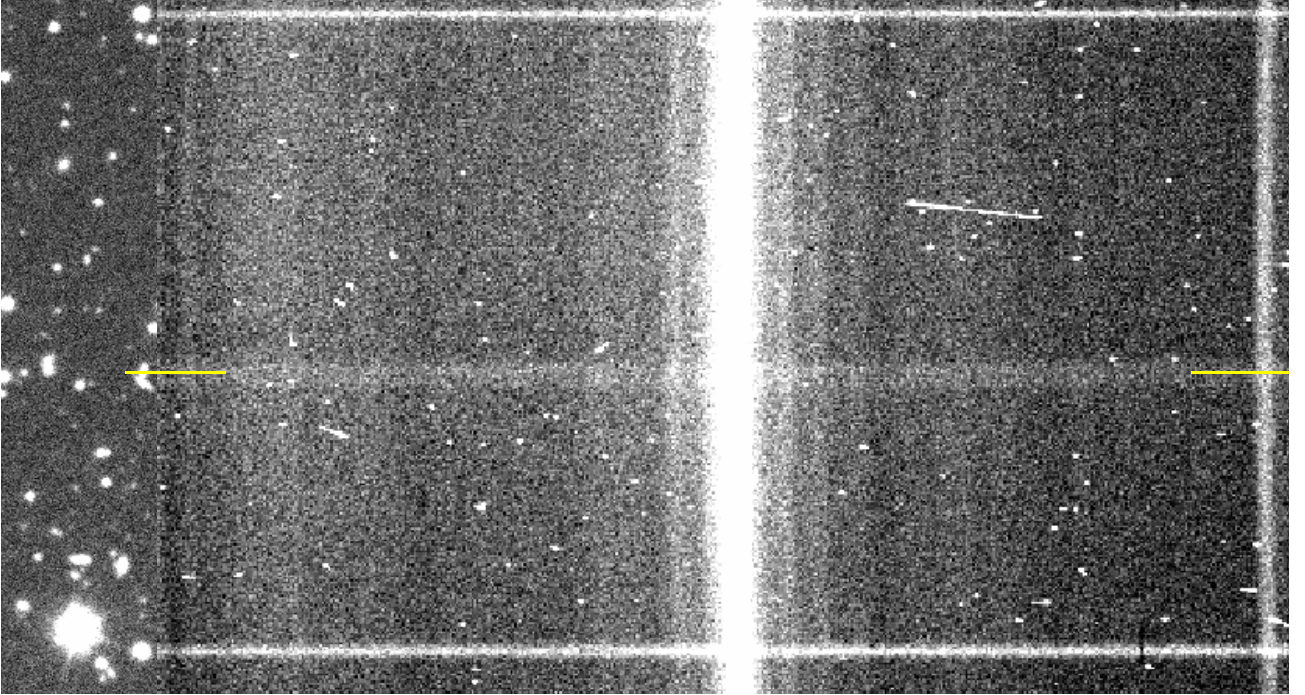


Figure 3.7: 2D trace from a SALT observation on 2023 December 11, with the DES DR2 image of the host galaxies positioned alongside to the left. The two reference stars used on that night are aligned with their respective traces, and two yellow line segments are aligned with the centre of the faint trace, from which we obtained the spectrum. The left line segment passes through the north galaxy, indicating that the spectrum obtained is associated with the north galaxy.

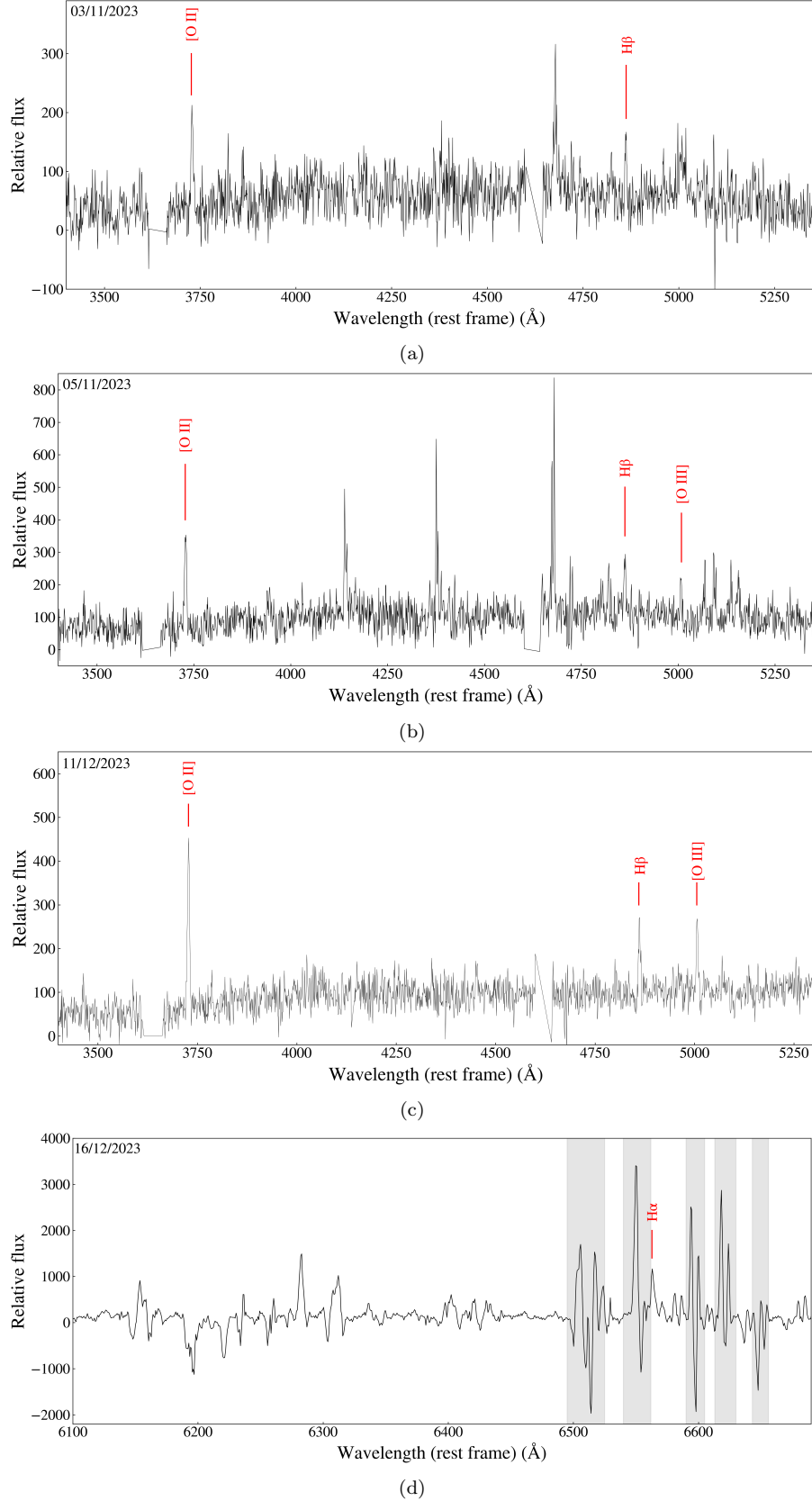


Figure 3.8: SALT spectra obtained over the course of four nights in late 2023. (a) Shows the average combined spectrum from the two observations on 2023 November 3. The unresolved [O II] doublet and H β lines are shown by the red lines at 3727 Å and 4862 Å, respectively. (b) Shows the average combined spectrum from the two observations on 2023 November 5. The [O II], H β and [O III] lines are all shown in red, at 3727 Å, 4862 Å and 5008 Å, respectively. (c) Shows the average combined spectrum from the two observations on 2023 December 11. The [O II], H β and [O III] lines are all shown in red, at 3727 Å, 4862 Å and 5008 Å, respectively. (d) Shows the average combined spectrum from the two observations on 2023 December 16. The H α emission line is indicated by a red line and the wavelength ranges that have been affected by sky lines are highlighted in grey.

telescope and the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescope, located on La Palma in the Canary Islands. The MAGIC telescopes are primarily designed for VHE gamma-ray detection, but can also perform optical observations using the central pixel, allowing for simultaneous optical and gamma-ray measurements during their operations. The authors detected five radio bursts and stacked the optical data around the arrival times of the bursts, obtaining optical fluence limits of 0.025 Jy ms on a timescale of 0.1 ms, 0.086 Jy ms on a timescale of 1 ms, 0.25 Jy ms on a timescale of 5 ms, and 0.36 Jy ms on a timescale of 10 ms. All of these limits were corrected for MW dust extinction and correspond to optical-to-radio fluence ratio limits of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.013 - 0.18$.

Niino et al. (2022) used Tomo-e Gozen (Sako et al., 2018), a high-speed camera mounted on the Kiso 105-cm Schmidt telescope, located at Kiso Observatory in Japan, to conduct optical observations of the repeater FRB 20190520B, which has a redshift of $z = 0.24$ (Niu et al., 2022), while simultaneously obtaining radio observations with the Five-hundred-meter Aperture Spherical radio Telescope (FAST). While they detected 11 radio bursts, no corresponding optical emission was found. They obtained MW-dust-extinction-corrected optical fluence limits as deep as 0.068 Jy ms on a timescale of 40.9 ms for the individual bursts. A limit of 0.029 Jy ms was obtained by averaging the optical flux of the 11 bursts. They also investigated the optical fluence on longer timescales, obtaining a fluence limit of 0.13 Jy ms on a timescale of 0.45 s, and 0.34 Jy ms on a timescale of 2.1 s. Their limits correspond to $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.23 - 2.1$ for individual bursts, and $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.20$ for the stacked optical limit.

Hiramatsu et al. (2023) conducted simultaneous, follow-up, and serendipitous archival survey observations of 15 well-localised FRBs, consisting of 7 repeating FRBs, 7 non-repeaters, and SGR 1935+2154. Their almost simultaneous observation with a 15 s integration time of the repeater FRB 20220912A, which has a redshift of $z = 0.077$ (Ravi et al., 2023) using Binospec (Fabricant et al., 2019) on the 6.5 m MMT Observatory in Arizona, USA, set a limit on the fluence ratio of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.00010$ on a timescale of ~ 0.4 s. They also observed the FRB using KeplerCam (Szentgyorgyi et al., 2005) on the 1.2 m Telescope at the Fred Lawrence Whipple Observatory in Arizona, USA, and the Sinistro camera on the 1 m telescope at the McDonald Observatory in Texas, USA, in the Las Cumbres Observatory (LCO; Brown et al. 2013a) network. They obtained a luminosity limit $\nu L_{\nu} \sim 2 \times 10^{41} \text{ erg s}^{-1}$ for their Binospec observation, while the luminosity limits for the same FRB that they obtain from simultaneous observations using KeplerCam and LCO range from $\sim (0.3 - 2.9) \times 10^{42} \text{ erg s}^{-1}$, which they report as being the deepest luminosity limits to date for an extragalactic FRB. These simultaneous luminosity limits correspond to fluence ratio limits as deep as $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.0010$.

Kilpatrick et al. (2023) used the ‘Alopeke high-cadence camera (Scott, 2018; Scott et al., 2021) on the Gemini North telescope, located on Mauna Kea in Hawaii, to obtain optical observations of two bursts from the repeater FRB 20180916B, which is at a redshift of $z = 0.034$ (Marcote et al., 2020). These observations occurred simultaneously with radio observations conducted by CHIME. They obtained MW-dust-extinction-corrected optical fluence limits on timescales of ~ 10.4 ms for each burst, corresponding to optical-to-radio fluence ratio limits of $F_{\text{opt}}/F_{\text{radio}} < 0.002 - 0.007$.

Trudu et al. (2023) conducted a multi-wavelength radio, optical and X/ γ -ray campaign on FRB 20180916B. They observed the FRB over the course of 8 months, using the Sardinia Radio Telescope (SRT) and the upgraded Giant Metrewave Radio Telescope (uGMRT; Gupta et al. 2017) for their radio observations. For their optical observations, they made use of the Aqueye+ fast photon counter (Barbieri et al., 2009; Zampieri et al., 2015), mounted on the Copernicus telescope, and the IFI+Iqueye fast photon counter (Naletto et al., 2009), mounted

on the Galileo telescope, both located in Asiago. Additionally, they made use of the Calar Alto 2.2 m telescope, the 2.5 m telescope at the Caucasian Mountain Observatory (CMO) of the Sternberg Astronomical Institute (SAI) Lomonosov Moscow State University (MSU), and the SiFAP2 fast photometer (Ghedina et al., 2018; Ambrosino et al., 2016) on the 3.6 m Telescopio Nazionale Galileo (TNG) in the Canary Islands. The deepest simultaneous optical fluence upper limits they obtained with Aqueye+ were 0.005 Jy ms on a timescale of 200 ms, and 0.009 Jy ms on a timescale of 30 s in November 2020. In August 2021, they obtained upper limits of 0.005 Jy ms on a timescale of 200 ms and 0.008 Jy ms on a timescale of 30 s. Their upper limits from IFI+Iqueye were 0.09 Jy ms on a timescale of 200 ms and 0.13 Jy ms on a timescale of 30 s. Their upper limits using TNG were 1.02 mJy ms on a timescale of 200 ms and 1.56 mJy ms on a timescale of 30 s. None of the upper limits reported by Trudu et al. (2023) were corrected for extinction. The FRB is located within a star forming region of a nearby spiral galaxy (Marcote et al., 2020), which could introduce extinction in addition to any Milky Way extinction. Based on the color excess map by Schlafly & Finkbeiner (2011), and using values for the V -band, the Milky Way extinction would be at least 2.7 mag. They set upper limits on the energy ratio $E_{\text{opt}}/E_{\text{radio}} < 1.3 \times 10^2 - 7.8 \times 10^2$, which they report as being the most stringent upper limits for FRB 20180916B to date.

Our fluence limit of 0.039 Jy ms is deeper than the limit obtained by Hardy et al. (2017) and those obtained by Niino et al. (2022) for individual bursts and on their timescales of 0.45 s and 2.1 s. The fluence ratio obtained by Hiramatsu et al. (2023) is deeper than ours and is on a shorter timescale. Our fluence limit is deeper than those obtained by the MAGIC Collaboration et al. (2018) on timescales greater than or equal to 1 ms. The almost simultaneous luminosity limit obtained by Hiramatsu et al. (2023) is two orders of magnitude deeper than ours. Kilpatrick et al. (2023) also obtained limits deeper than our own and on much shorter timescales. The energy ratio limits obtained by Trudu et al. (2023) are 3 orders of magnitude deeper than our own. Their Aqueye+ and SiFAP2 fluence limits are also deeper than ours on both of their considered timescales, as are their deepest luminosity limits. The fluence ratio limits of the previous works discussed, where available, along with our own limits, are presented in Table 3.4, and the associated luminosity limits are shown in Figure 3.9.

We note that the aforementioned optical limits were all for repeater FRBs, whereas ours are for a so far non-repeating burst. Hiramatsu et al. (2023) did some analysis based on archival optical observations of non-repeating FRBs, but all of the optical observations of one-offs available to them, had delays $\gtrsim 10^4$ s with respect to the time of the bursts. Núñez et al. (2021) were able to obtain optical observations of the non-repeating FRB 20190711 using the Las Cumbres Observatory Global Telescope (LCOGT) network (Brown et al., 2013b), but their 60 s exposures commenced almost two hours after the FRB’s arrival time. Our optical observation time delay of ~ 3.4 s is by far the smallest such delay for a non-repeater to date. All of the optical-to-radio fluence ratios for non-repeaters in Hiramatsu et al. (2023) are $\gtrsim 1$, and as such our value of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.023$ is a significant improvement.

Table 3.4: Fluence ratio limits for previous studies discussed, along with the limit obtained in this work. Aside from our own limit, all of the other limits above are for repeating FRBs. t_{radio} refers to the duration of the observed radio emission, and t_{opt} refers to the optical timescale.

Work	$F_{\text{opt}}/F_{\text{radio}}$	Repeater	t_{radio} (ms)	t_{opt} (s)	Strictly simultaneous
Hardy et al. (2017)	$\lesssim 0.28$	Yes	$\sim 1.8 - 5.1$	0.1414	Yes
MAGIC Collaboration et al. (2018)	$\lesssim 0.013 - 0.18$	Yes	$\sim 1.2 - 5.7$	0.0001 – 0.01	Yes
Niino et al. (2022)	$\lesssim 0.20 - 2.1$	Yes	—	0.0409 – 2.1	Yes
Hiramatsu et al. (2023)	$\lesssim 0.00010 - 0.0010$	Yes	$\sim 0.01 - 300$	0.4 – 400	Mostly
Kilpatrick et al. (2023)	$< 0.0020 - 0.0070$	Yes	~ 2.7	0.0104	Yes
This work	$\lesssim 0.023; \lesssim 0.43$	No	~ 10.9	3.4; 63.4	No

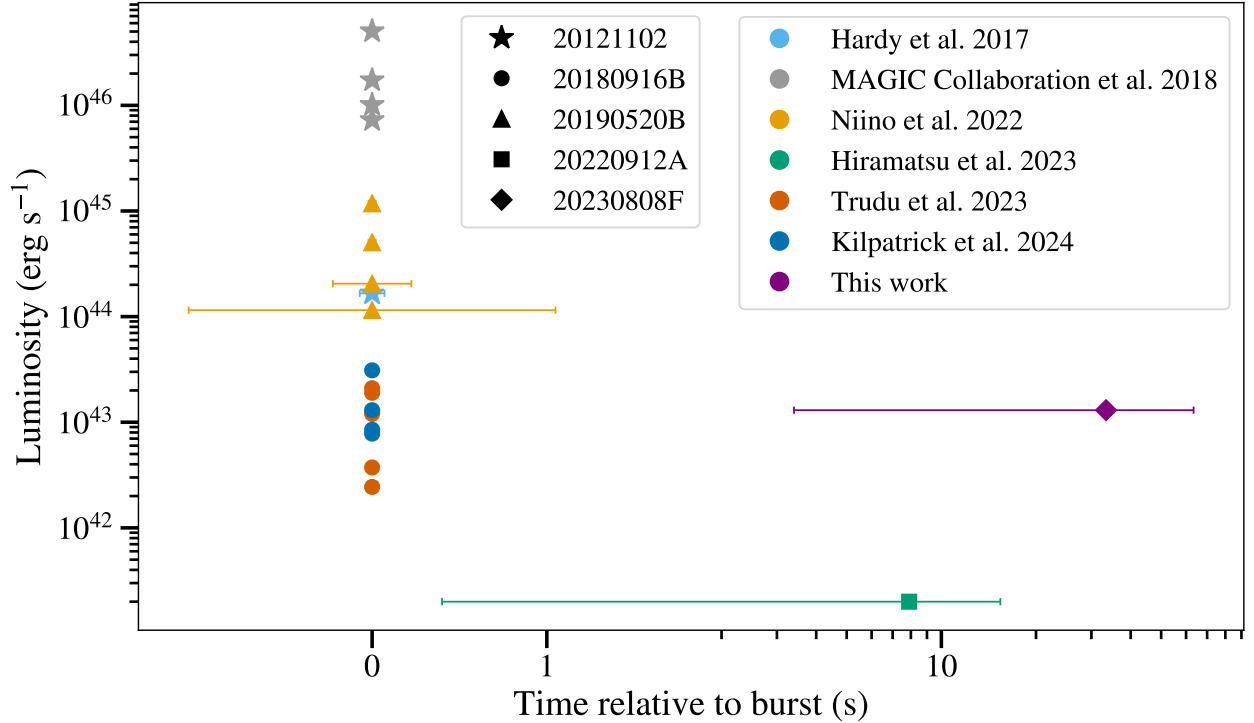


Figure 3.9: Luminosity limits obtained by Hardy et al. (2017), the MAGIC Collaboration et al. (2018), Niino et al. (2022), Hiramatsu et al. (2023), Trudu et al. (2023) and Kilpatrick et al. (2023), along with our luminosity limit. Limits for different FRBs are represented by different shapes, while those from different works are shown by different colours. The second highest Niino et al. (2022) luminosity limit is the one which is based on averaging the optical flux of multiple bursts. The x-axis is linear near zero to display upper limits centered on the FRB arrival time, and then transitions to a logarithmic scale to accommodate larger timescales.

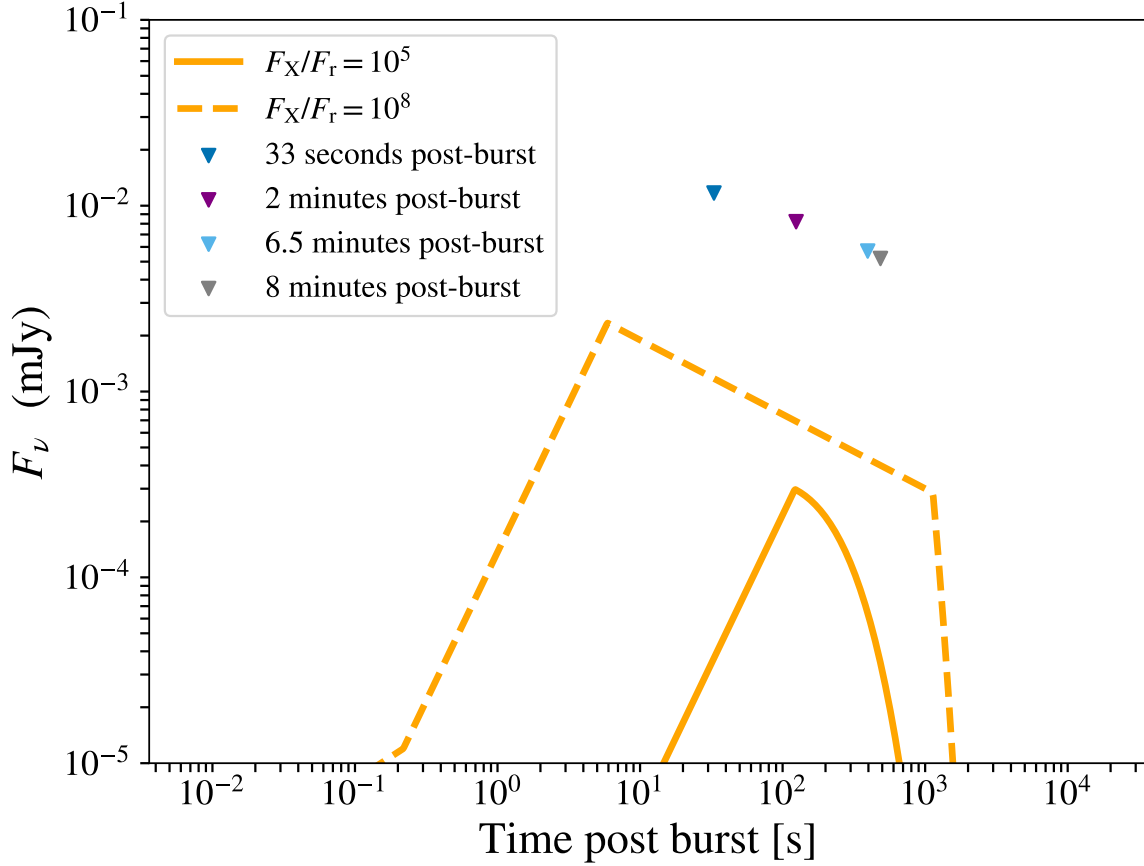


Figure 3.10: Optical afterglow predictions for the synchrotron maser model, as prescribed by Margalit et al. (2020) and Cooper et al. (2022), using X-ray/radio flux ratios of 10^5 and 10^8 . For this model, we used the luminosity value for FRB 20230808F that was calculated using the burst bandwidth. The upper flux limits from our earliest post-FRB MeerLICHT observations are represented by the inverted triangles.

3.5.2 Constraints on the synchrotron maser model

Following the afterglow prescription outlined in Metzger et al. (2019), Margalit et al. (2020) and Cooper et al. (2022), we used the observed properties of FRB 20230808F to make a prediction for the optical afterglow expected within the maser shock framework at MeerLICHT’s q -band frequency. The predicted afterglow, along with our MeerLICHT q -band flux upper limits obtained within the first 20 minutes post-burst, is shown in Figure 3.10. We assume an unseen early X-ray afterglow with a given X-ray/radio flux luminosity, in order to normalise the rest of the afterglow, using values of $L_{\text{X-ray}}/L_{\text{radio}} = 10^5$ and $L_{\text{X-ray}}/L_{\text{radio}} = 10^8$. Our upper limits in this case, at such a large cosmological distance, are not constraining for the maser shock model, although they would be constraining for FRBs at lower redshifts, or for deeper optical flux limits. Assuming the same flux limits obtained in this work, a redshift of $z \lesssim 0.15$ would constrain the synchrotron maser model using $L_{\text{X-ray}}/L_{\text{radio}} = 10^8$.

3.5.3 Host galaxy and redshift

From our observations of the FRB region using SALT, we were able to obtain a spectroscopic redshift of $z_{\text{spec}} = 0.3472 \pm 0.0002$, and we took this to be the redshift of both galaxies and thus of FRB 20230808F. We conclude that the two potential host galaxies are a close pair, and

possibly interacting. Furthermore, we conclude that either the host galaxy, a foreground galaxy, or the FRB environment contribute significantly to the DM, scattering timescale, and rotation measure of the burst.

3.6 Summary and conclusions

We obtained an almost simultaneous optical limit associated with the newly discovered FRB 20230808F. We set a flux limit of $f_{\text{AB},q} < 11.7 \mu\text{Jy}$ for a 60 s exposure starting ~ 3.4 s after the burst, which translates to a luminosity limit of $\nu L_\nu \sim 1.3 \times 10^{43} \text{ erg s}^{-1}$. This is deeper than most other luminosity limits for optical emission associated with extragalactic FRBs, surpassed only by limits for repeaters obtained by Hiramatsu et al. (2023), Kilpatrick et al. (2023) and Trudu et al. (2023). Our limits were not constraining for the synchrotron maser model, but would be for an FRB at a lower redshift, or if our flux limits were deeper. The FRB was localised to a pair of close, possibly interacting galaxies at a redshift $z_{\text{spec}} = 0.3472 \pm 0.0002$, and the scattering, DM and RM were all found to have significant extragalactic contributions, from either the FRB environment, host galaxy, or a foreground galaxy. We have significantly improved upon previous ratios of $F_{\text{opt}}/F_{\text{radio}}$ for non-repeating FRBs with our $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.023$, when the optical fluence is calculated on a timescale equal to the delay between the FRB arrival time and the start of the optical exposure. Our delay of ~ 3.4 s is the shortest delay for an optical observation of a non-repeating FRB. We have demonstrated the ability of MeerLICHT’s observing strategy when it comes to achieving almost simultaneous observations of FRBs, which has the potential to yield strictly simultaneous optical observations, even for non-repeating FRBs, in the future. With this setup, there are further opportunities for simultaneous MeerKAT-MeerLICHT observations of FRBs, and this should allow us to set more constraining limits on any optical emission associated with these enigmatic bursts.

Table 3.5: Upper limits on optical emission for FRB 20230808F, corrected for MW dust extinction.

Filter	Upper limit or detection magnitude (AB)	Upper limit or detection flux (μJy)	Filter	Upper limit or detection magnitude (AB)	Upper limit or detection flux (μJy)
1 min before			1 min after		
<i>u</i>	19.7	46.9	<i>q</i>	21.2	11.7
5 min before			5 min after		
<i>u</i>	19.7	46.9	<i>q</i>	21.6	8.2
<i>q</i>	21.7	7.5	<i>r</i>	20.6	20.0
<i>i</i>	20.3	28.5	<i>z</i>	19.2	74.7
15 min before			15 min after		
<i>u</i>	19.7	46.9	<i>u</i>	19.5	57.0
<i>g</i>	20.9	16.5	<i>g</i>	20.7	19.4
<i>q</i>	22.2	4.7	<i>q</i>	22.0	5.7
<i>r</i>	20.7	19.1	<i>r</i>	20.6	20.0
<i>i</i>	20.3	28.5	<i>i</i>	20.0	36.4
<i>z</i>	19.3	68.8	<i>z</i>	19.2	74.7
20 min before			20 min after		
<i>u</i>	20.1	32.9	<i>u</i>	19.5	57.0

Filter	Upper limit or detection magnitude (AB)	Upper limit or detection flux (μ Jy)	Filter	Upper limit or detection magnitude (AB)	Upper limit or detection flux (μ Jy)
<i>g</i>	20.9	16.5	<i>g</i>	20.7	19.4
<i>q</i>	22.4	4.0	<i>q</i>	22.1	5.2
<i>r</i>	20.7	19.1	<i>r</i>	20.9	15.3
<i>i</i>	20.6	20.0	<i>i</i>	20.0	36.4
<i>z</i>	19.3	68.8	<i>z</i>	19.2	74.7
2023-08-01			2023-08-02		
<i>u</i>	20.4	26.1	<i>u</i>	19.8	42.2
<i>g</i>	21.2	12.1	<i>g</i>	20.7	18.4
<i>q</i>	22.5	3.7	<i>q</i>	22.1	5.4
<i>r</i>	21.2	12.0	<i>r</i>	20.8	17.3
<i>i</i>	21.1	13.1	<i>i</i>	20.5	22.1
<i>z</i>	20.3	28.5	<i>z</i>	19.6	50.2
2023-09-06			2023-10-01		
<i>u</i>	22.0	6.0	<i>u</i>	19.0	95.5
<i>g</i>	22.5	3.7	<i>q</i>	20.5	22.5
<i>q</i>	22.3 ± 0.2	4.3 ± 0.6	<i>i</i>	19.9	39.9
<i>i</i>	21.7 ± 0.2	7.5 ± 1.6			
<i>z</i>	21.3	10.7			
2023-10-02			2023-10-03		
<i>u</i>	19.1	85.9	<i>u</i>	19.5	57.5
<i>q</i>	20.6	20.1	<i>q</i>	21.4	10.1
<i>i</i>	19.8	44.7	<i>i</i>	20.1	32.0
2023-10-04			2023-10-17		
<i>u</i>	18.5	151.0	<i>u</i>	20.6	21.8
<i>q</i>	20.4	24.7	<i>q</i>	22.2 ± 0.3	4.7 ± 1.3
<i>i</i>	19.1	85.8	<i>i</i>	21.2	12.4
2023-10-18			2023-10-19		
<i>u</i>	20.0	37.4	<i>u</i>	21.9	6.0
<i>q</i>	21.8	6.9	<i>q</i>	22.3 ± 0.1	4.3 ± 0.6
<i>i</i>	20.2	29.7	<i>i</i>	21.8 ± 0.3	6.7 ± 1.6
2023-10-25			2023-10-26		
<i>u</i>	21.1	13.8	<i>u</i>	20.1	33.3
<i>q</i>	22.5	3.8	<i>q</i>	21.5	8.9
<i>i</i>	21.6	8.5	<i>i</i>	20.8	17.7
2023-10-29			2023-10-30		
<i>q</i>	20.0	37.0	<i>u</i>	20.0	37.5
			<i>q</i>	21.3	10.7
			<i>i</i>	20.6	21.0

Filter	Upper limit or detection magnitude (AB)	Upper limit or detection flux (μJy)	Filter	Upper limit or detection magnitude (AB)	Upper limit or detection flux (μJy)
2023-10-31			2023-11-01		
<i>u</i>	20.0	37.1	<i>u</i>	19.3	71.2
<i>q</i>	21.4	9.7	<i>q</i>	21.4	9.9
<i>i</i>	19.8	44.7			
2023-11-02			2023-11-04		
<i>u</i>	19.2	78.1	<i>u</i>	21.0	14.0
<i>q</i>	21.0	14.7	<i>q</i>	22.3 ± 0.2	4.2 ± 0.9
<i>i</i>	19.5	59.4	<i>i</i>	21.5	8.9
2023-11-07			3 months post-FRB		
<i>u</i>	20.7	19.9	<i>u</i>	22.3	4.3
<i>q</i>	21.9 ± 0.2	6.5 ± 1.3	<i>g</i>	22.4	3.8
<i>i</i>	21.0	14.5	<i>q</i>	23.8 ± 0.1	1.1 ± 0.1
			<i>r</i>	21.0	15.1
			<i>i</i>	22.0 ± 0.2	5.7 ± 1.1
			<i>z</i>	21.3	10.7

Chapter 4

FRB 20240619D - the first repeater discovered by MeerTRAP

4.1 Discovery of FRB 20240619D

Only around 60 repeaters have been published as of April 2025, as mentioned in Section 1.3, which is ~ 3 per cent of all FRBs (Pleunis et al., 2021). Most of these have been discovered by CHIME/FRB, which observes in the 400 – 800 MHz band, making it uncertain whether the repeater fraction remains consistent across all radio frequencies. Over the course of its operations, MeerKAT had never discovered a repeating FRB, until the early hours of 2024 June 19, when MeerTRAP (described in detail in Chapter 2) detected three bursts in the space of two minutes in the L -band (Tian et al., 2024). These belonged to the first ever repeating FRB to be discovered by MeerKAT, FRB 20240619D. The bursts each triggered a transient buffer data dump, allowing for initial localisation using the TB imaging pipeline (Rajwade et al., 2024). The parameters of these three bursts are summarised in Table 4.1.

4.2 MeerKAT observations

After the discovery of FRB 20240619D, MeerKAT Director’s Discretionary Time (DDT) was applied for, and a total of 4 hours for follow-up observations of FRB 20240619D were awarded (DDT-20240625-JT-01). These observations were carried out over the course of two days: with 1 hour each in the L and S bands, on 2024 June 26 at 00:09 UTC, and 2 hours simultaneously at UHF and L -band on 2024 June 28 at 00:30 UTC. The FRB was localised to a position of RA (J2000) = $19^{\text{h}}49^{\text{m}}29^{\text{s}}.21 \pm 0^{\text{s}}.05$ and Dec (J2000) = $-25^{\circ}12'49''.40 \pm 0''.70$, using the voltage data of a bright S -band burst (Tian et al., in prep).

Table 4.1: Detection characteristics of the first 3 bursts detected by MeerTRAP for the repeating FRB 20240619D.

Date and time (UTC)	S/N	DM (pc cm^{-3})
2024-06-19 00:41:01	28	486.8
2024-06-19 00:41:17	22	480.7
2024-06-19 00:42:13	14	471.9

During the observations on 2024 June 28, 46 bursts were detected in the UHF, and 108 were detected in the L -band. For these observations, MeerTRAP was operating at UHF, while the L -band data had to be searched for bursts offline, using data from the Pulsar Timing User Supplied Equipment (PTUSE; Bailes et al. 2020). All of the L -band bursts were de-dispersed using a DM of 464.9 pc cm^{-3} . This DM value is lower than the three DMs presented in Table 4.1, which were the S/N maximising DMs of those individual bursts. However, given that bursts from FRB 20240619D display complex structure, the DM was determined using a method that optimises structure rather than S/N. The S/Ns for the UHF bursts range from $8.13 - 49.76$, while for the L -band bursts they range from $6.59 - 579.74$. Twelve of the bursts were detected simultaneously across the UHF and L -band, meaning that a total of 142 unique bursts were detected.

4.3 MeerLICHT observations

MeerLICHT was not observing on 2024 June 19, when FRB 20240619D was first discovered, due to unfavourable weather. During the first follow-up observation of the FRB on 2024 June 26, MeerLICHT was synced with MeerKAT, but the incorrect field ID was chosen by MeerLICHT, meaning that the FRB coordinates were not observed. MeerLICHT operates in a snap-to-grid mode, selecting the field ID whose central coordinates are closest to the desired observation coordinates. The FRB coordinates are at the edge of MeerLICHT’s field 05045, which has central coordinates of RA (J2000) = $19^{\text{h}}53^{\text{m}}08^{\text{s}}.57$, Dec (J2000) = $-24^{\circ}41'06''.4$, but the automated MeerLICHT scheduler selected field 05044 - with central coordinates RA (J2000) = $19^{\text{h}}46^{\text{m}}17^{\text{s}}.15$, Dec (J2000) = $-24^{\circ}41'06''.4$ - as the field ID whose central coordinates were closest to the FRB coordinates. The selection by MeerLICHT’s scheduler of the incorrect field was due to flexure in MeerLICHT’s system and a pointing inaccuracy, as well as an offset to correct the ADC controller, all of which introduce approximately $1'$ of jitter on the actual positioning. Normally, this is not a problem for MeerLICHT’s large FoV, but in such a case as this one, where the FRB coordinates were so close to the edge of a particular field, it can - and did - result in the wrong field being chosen. Once we became aware of this issue, and knowing that further observations would be taking place on 2024 June 28, we scheduled MeerLICHT to specifically observe field 05045 for approximately 5 hours, from June 27 23:00 UT to June 28 04:00 UT, and with each exposure being 15 s long. The observations were scheduled to alternate between the u , q , and i bands over the course of the observing block, with 20 exposures per filter taking place before switching to the next filter. The observations started with 20 q -band exposures, followed by 20 u -band exposures, then 20 q -band exposures again, and lastly 20 i -band exposures, and so on, with a set of 20 q -band exposures always being taken in between the sets of u - and i -band exposures. We also scheduled several long (300 s) exposures of the field to take place before the series of short exposures, so as to obtain images to generate a deep co-add of the field for later image subtraction. The typical limiting magnitudes for the long exposures in each of the filters were ~ 20.7 for the u -band, ~ 21.7 for the q -band, and ~ 20.7 for the i -band, while for the short exposures the typical limiting magnitude per filter was ~ 17.6 for the u -band, ~ 19.4 for the q -band, and ~ 18.3 for the i -band.

4.4 Analysis of MeerLICHT data

After the MeerKAT and MeerLICHT observations had both taken place on 2024 June 28, we started by creating a deep co-add in each filter using the `buildref.py`¹ co-adding routine. The

¹<https://github.com/pmvreeswijk/BlackBOX/blob/main/buildref.py>

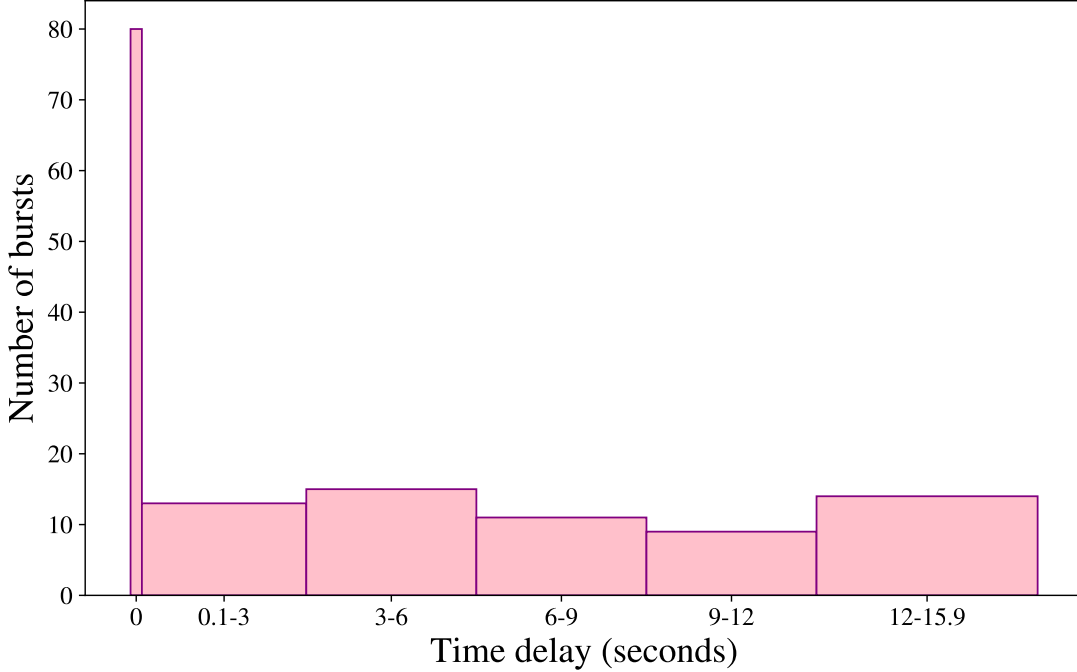


Figure 4.1: Histogram showing the distribution of delay times between the burst arrival times and the start of MeerLICHT observations. The first narrow bin shows all of the bursts for which we have strictly simultaneous MeerLICHT observations, meaning that the arrival time of a burst fell within a 15 s MeerLICHT exposure, while the other bins contain all of the bursts where there was a delay between the arrival time and the start of an optical exposure. The bursts which were observed across both the UHF and L -band have only been accounted for once.

routine takes in a given list of images, and co-adds all those that satisfy the quality control (QC) flag constraint, which can be adjusted according to the specific case. The possible QC flags for MeerLICHT images are green, yellow, orange and red, with red meaning that an image is unusable. We used the default QC flag constraint when running `buildref.py`, which is orange, meaning that any image with a QC flag of orange or better is included in the co-add. Then, we determined which of the MeerLICHT exposures contained the arrival times of the MeerKAT bursts. We did this by first correcting all of the burst arrival times to infinite frequency. For both the UHF and L -band bursts, we used the L -band de-dispersion DM of 464.9 pc cm^{-3} . We then checked the delays between all of the UHF and L -band bursts to determine whether any of the bursts detected were seen in both bands. We found 12 pairs of bursts with a separation in corrected MJD of less than $\sim 60 \text{ ms}$, and we determined that these were bursts that were detected across both bands. The rest of the bursts appeared to be unique. We then used a custom Python script to take in each corrected burst MJD, and determine whether this fell within one of the MeerLICHT exposures. We found that some 15 s MeerLICHT exposures contained more than one burst. Out of a total of 142 unique bursts, we were observing strictly simultaneously in the optical for 80 of them. For the other 62, MeerLICHT was not taking an exposure at the arrival time of the burst, and was instead reading out data from the previous exposure to disk. The distribution of delay times between the burst TOA and the start of the MeerLICHT exposure for all of the bursts is shown in Figure 4.1.

Next, we created an “on” image for each of the MeerLICHT filters in which observations were taken, by co-adding all of the MeerLICHT images which contained the corrected MJD of one or more bursts, and an “off” image per filter which used all of the MeerLICHT images containing no

burst TOAs that were taken while MeerKAT was also observing the FRB field. We performed image subtraction on the co-added images and on all of the individual MeerLICHT images taken over the course of the observing period, using the deep co-add we made as a reference image. We then ran forced photometry using `forcephot.py`² on all of the image subtraction products. The module takes in a given set of coordinates, and can be run on specific images. Forced photometry is then run at the specified coordinates, yielding the flux at the position, the error on the flux, the signal-to-noise ratio, and the limiting magnitude at the significance level that has been specified by the user. We used a significance level of 3σ for all forced photometry relating to FRB 20240619D.

The forced photometry routine yielded a limiting magnitude at a 3σ significance level for all of the images, and no positive or negative detections were found at a $S/N > 3$. We corrected for MW extinction as described in Section 3.3.2, and then converted the limiting magnitudes to fluxes using:

$$m_{AB} = -2.5 \log \left(\frac{f}{3631 \text{ Jy}} \right). \quad (4.1)$$

We also calculated fluences for all of the bursts. For bursts where we obtained strictly simultaneous MeerLICHT images, we calculated the fluence limit on a timescale of 15 s, equal to the length of the exposure. For bursts where there was a delay between the burst arrival time and the start of a MeerLICHT exposure, we calculated the corresponding fluences using two different timescales: we first used just the length of the delay as the timescale in the calculation, and then we used the length of the delay added to the integration time of the MeerLICHT image. The reason we chose to use both timescales was so that we can compare our limits to non-simultaneous optical fluence limits calculated by Hiramatsu et al. (2023), where they used just the delay time between radio and optical observations, and so that we could also present fluence limits where we have retained consistency with our strictly simultaneous fluence limit calculations, by including the full integration time. Hereafter, we will use the following abbreviations:

- “FS” for strictly simultaneous optical fluence limits,
- “FD” for non-simultaneous optical fluence limits where the timescale was just the delay time, and
- “FDE” for non-simultaneous optical fluence limits where the timescale was the delay time added to the integration time.

In some instances, a single MeerLICHT exposure coincided with more than one burst and/or was the closest available image for a burst lacking a strictly simultaneous optical observation. In such cases, we use the total flux limit from the image for each burst it pertains to. However, when calculating the fluence limit, we apply the specific timescale relevant to each burst individually. The calculated fluence limits for all of the bursts are displayed in Figure 4.2. For the non-simultaneous bursts, the fluence limits calculated on the longer timescale (the delay time added to the full integration time) are displayed.

If there is optical emission associated with FRBs, then the total flux from a single short MeerLICHT image should, in this scenario, reflect the combined contributions of all bursts occurring within the exposure time. But since we lack information on how the flux contributions from each burst might differ, or on how or if they might correlate with the radio fluxes, we conservatively use the total flux for any and all relevant bursts contained within a single MeerLICHT image, or for which it is the closest in time.

²https://github.com/pmvreeswijk/ZOGY/blob/main/force_phot.py

Table 4.2: Summed limiting magnitudes and optical flux and fluence limits for co-added “on” images. For the fluence limits, we multiplied the flux limit from each co-add by the full exposure time of the co-add. Then, for the average fluence limits, we divided the fluence limit by the number of bursts contained within each co-add.

Filter	Limiting mag (AB)	Flux (μJy)	Fluence (Jy ms)	Average fluence (Jy ms)
<i>u</i>	17.80	275.68	41.35	4.14
<i>q</i>	21.36	10.39	4.99	0.10
<i>i</i>	20.27	28.42	8.10	0.37

Table 4.3: Summed limiting magnitudes and optical flux and fluence limits for co-added “off” images.

Filter	Limiting mag (AB)	Flux (μJy)	Fluence (Jy ms)
<i>u</i>	18.40	158.31	104.48
<i>q</i>	21.80	6.93	7.80
<i>i</i>	20.72	18.64	11.47

Across all of the individual bursts we analysed, we detected no optical counterpart to FRB 20240619D. We obtained optical fluence limits in the range of $\sim 0.04 - 26.99$ Jy ms. The flux and fluence limits for the co-added “on” and “off” images in the *q*-, *u*- and *i*-bands are shown in Tables 4.2 and 4.3, while a summary of the mean and spread of the flux limits of the individual bursts is presented in Tables 4.4 and 4.5. We calculated the average “on” flux limit across all of the images which contained burst arrival times. We also calculated the average “on” flux limit per burst, by including each flux measurement in the calculation of the average, as many times as there were burst arrival times contained within the exposure time. Then we calculated a summed “on” flux limit per MeerLICHT filter from our co-added “on” image, and a fluence limit per filter from this by multiplying by the total timescale of the co-add. We did the same for the co-added “off” image. We also calculated the mean “off” flux limit, by averaging across the MeerLICHT images which contained no burst arrival times. Lastly, we calculated the ratio of optical-to-radio fluence $F_{\text{opt}}/F_{\text{radio}}$ for all of the bursts.

The burst time of arrival, radio fluence, optical limiting magnitude, and optical flux and fluence limits for all 142 unique bursts are presented in Table 4.7.

Our deepest FS was 0.76 Jy ms. This value was calculated on a timescale of 15 s, and was for bursts UHF 2 and L 12 (81). These are two separate bursts, but they have the same fluence upper limit because they were both covered simultaneously by the same MeerLICHT exposure, and thus both had the same flux upper limit on the same timescale. The deepest simultaneous optical-to-radio fluence ratio limit we obtained was $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.034$, which was for burst L 13 (82).

For the non-simultaneous bursts, our deepest FDE was 0.91 Jy ms for burst L 47 (116), and the deepest non-simultaneous optical-to-radio fluence ratio limit was then $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.11$ for burst L 49 (118). When using just the delay time as the timescale for non-simultaneous fluence limits, the deepest FD we obtain is 0.04 Jy ms for burst UHF 26. UHF 26 had no strictly simultaneous optical observation, with a delay of ~ 0.6 s between the burst arrival time and the

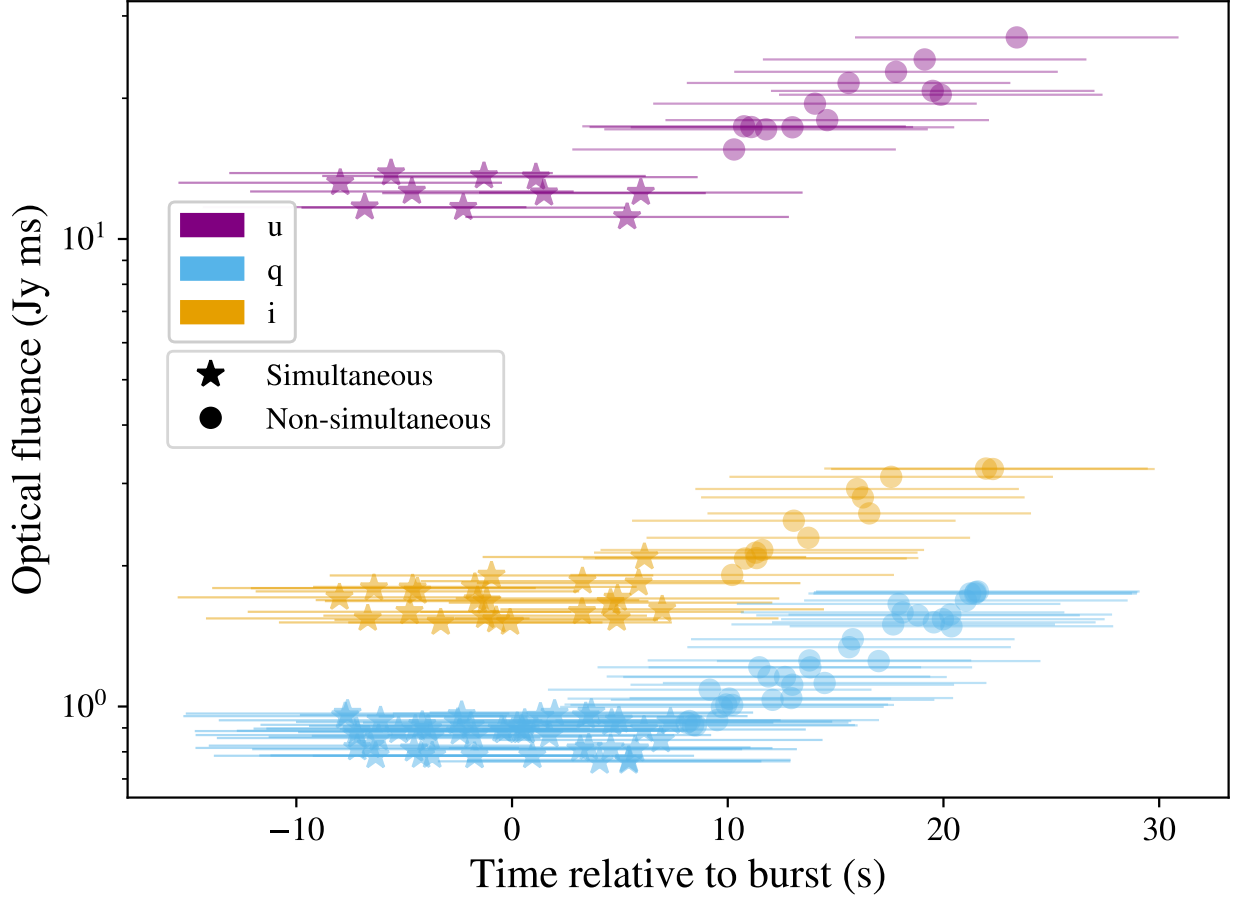


Figure 4.2: Optical fluence limits obtained for all of the individual bursts of FRB 20240619D. The different MeerLICHT filters are represented by the different colours, while the different symbols indicate whether the measurement was for a burst for which we had a strictly simultaneous optical observation, or for one where we had a non-simultaneous optical observation. The plotted fluence limits for non-simultaneous bursts are the ones which were calculated using the delay time added to the full integration time.

start of the MeerLICHT exposure, and the limit of 0.04 Jy ms was obtained when using just the delay time in the fluence limit calculation. It corresponds to an optical-to-radio fluence ratio limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.015$, which was also our deepest fluence ratio limit for an individual burst.

When we take the fluence limit from our q -band “on” image, and average it across the number of bursts contained in the image (48), we get a summed and averaged strictly simultaneous limit of 0.10 Jy ms, which corresponds to an optical-to-radio fluence ratio limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.037$. Hereafter, we will refer to the summed and averaged strictly simultaneous optical fluence limit as “FSS”.

4.5 Comparison to previous optical limits

If we consider our deepest optical fluence limit to be 0.04 Jy ms, which is the limit obtained for burst UHF 26, where just the time delay was used as the timescale (FD), then our deepest optical fluence limit and fluence ratio limit are deeper than those obtained by Hardy et al. (2017), which were 0.17 Jy ms and $\lesssim 0.28$, respectively.

Table 4.4: Average optical flux limits for bursts with strictly simultaneous optical observations.

Filter	Average flux per burst (μJy)	σ_{flux} per burst (μJy)	Average flux per “on” image (μJy)	σ_{flux} per image (μJy)
<i>u</i>	843.22	61.49	843.22	61.49
<i>q</i>	58.21	4.11	57.89	4.25
<i>i</i>	113.02	9.91	114.54	9.78

Table 4.5: Average optical flux limits for images containing no bursts.

Filter	Average flux per “off” image (μJy)	σ_{flux} (μJy)
<i>u</i>	865.48	72.00
<i>q</i>	57.80	4.27
<i>i</i>	113.41	5.89

Of the limits reported by the MAGIC Collaboration et al. (2018), our FD is deeper than all except their shortest timescale (0.1 ms) limit of 0.025 Jy ms. For the rest of their timescales, all of which are 10 ms or smaller, we obtained deeper limits despite our comparatively long timescale of ~ 0.6 s, which was the delay time between the burst TOA and the start of the MeerLICHT exposure. Their deepest optical-to-radio fluence ratio limit was $\lesssim 0.013$, which is deeper than the ratio we obtained.

Our FD of 0.04 Jy ms is deeper than all but one of the limits obtained by Niino et al. (2022). On a timescale of 0.45 s, more similar to our own timescale of 0.6 s, they obtained a fluence limit of 0.13 Jy ms. Our corresponding fluence ratio limit is deeper than any of the fluence ratio limits obtained by Niino et al. (2022), the deepest of which was $\lesssim 0.20$.

Hiramatsu et al. (2023) obtained fluence ratio limits deeper than our own, with a limit as deep as $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.00010$ on a timescale of ~ 0.4 s. This was for an optical exposure which was 15 s long and started ~ 0.4 s after the FRB arrival time, and their fluence calculation only considered the ~ 0.4 s, with no inclusion of the integration time.

The optical-to-radio fluence ratio limits reported by Kilpatrick et al. (2023) of $F_{\text{opt}}/F_{\text{radio}} < 0.002 - 0.007$ and obtained on timescales of ~ 10.4 ms for each burst, are deeper than the optical-to-radio fluence ratio limit of $\lesssim 0.015$ associated with our FD.

If we instead consider our deepest individual strictly simultaneous optical fluence limit (FS) and deepest strictly simultaneous optical-to-radio fluence ratio limit, then our optical fluence limit is surpassed by that obtained by Hardy et al. (2017), although our optical-to-radio fluence ratio limit is deeper than theirs, even though ours is on a timescale of 15 s as opposed to their timescale of 141.4 ms. All of the optical fluence limits obtained by the MAGIC Collaboration et al. (2018) are deeper than our deepest FS, although our fluence ratio limit is deeper than some of those reported by the MAGIC Collaboration et al. (2018). The fluence ratio limits obtained by Niino et al. (2022) were not as deep as ours, despite our longer timescale, although their optical fluence limits were all deeper than our deepest FS. The fluence ratio limits obtained by Hiramatsu et al. (2023) are deeper than ours, as are those obtained by Kilpatrick et al. (2023).

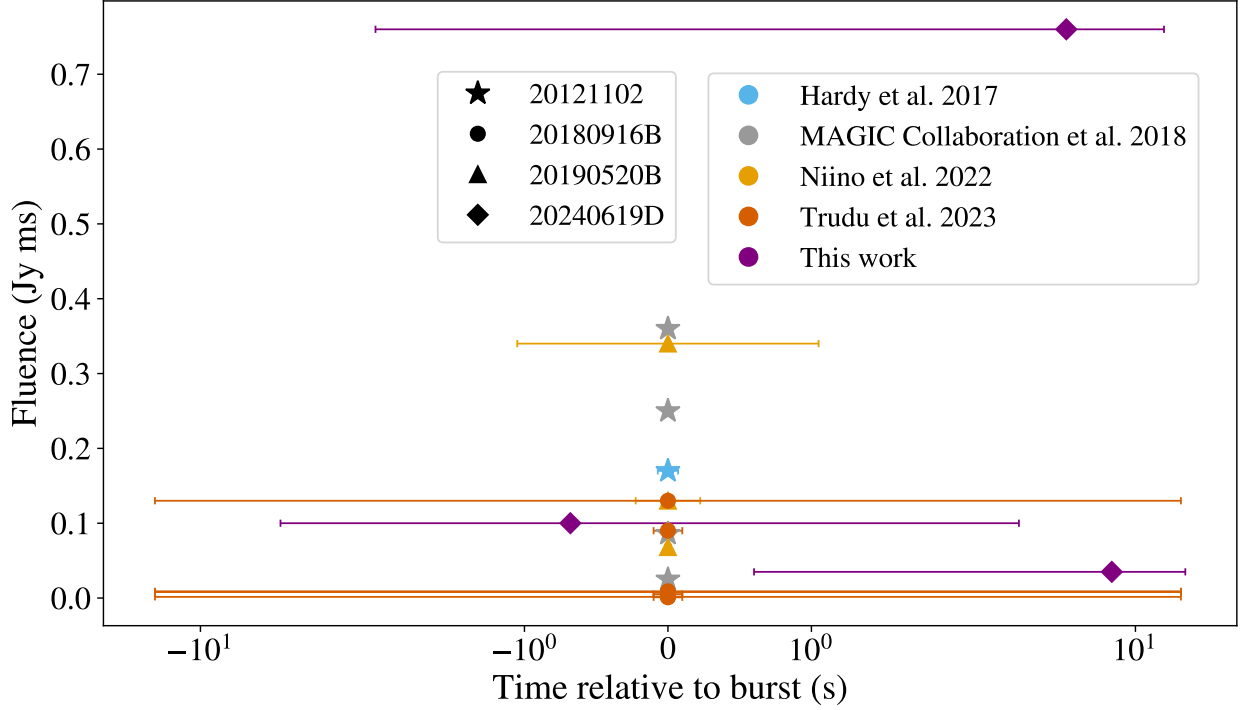


Figure 4.3: Optical fluence limits obtained by Hardy et al. (2017), the MAGIC Collaboration et al. (2018), Niino et al. (2022), and Trudu et al. (2023), along with our deepest individual simultaneous (FS), deepest summed simultaneous (FSS), and deepest individual non-simultaneous (FD) limits for FRB 20240619D. The x-axis is linear near zero to display upper limits centered on the FRB arrival time, and then transitions to a logarithmic scale to accommodate larger timescales. It is important to note that the lowest of our three limits shown here, the FD limit, was calculated on a timescale of 0.6 s, and does not include the 15 s integration time of the image exposure.

Lastly, we consider our summed and averaged strictly simultaneous optical fluence limit (FSS) of 0.10 Jy ms. This fluence limit is not as deep as the summed and averaged optical limit of 0.029 Jy ms obtained by Niino et al. (2022). However, our corresponding fluence ratio limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.037$ is deeper than their corresponding fluence ratio limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 0.20$. Our stacked fluence limit and fluence ratio limit are deeper than those obtained by Hardy et al. (2017). Our fluence limit and fluence ratio limit are surpassed by some of the limits obtained by the MAGIC Collaboration et al. (2018), while the fluence ratio limits obtained by Hiramatsu et al. (2023) and Kilpatrick et al. (2023) surpass our own. Our FSS is deeper than the shallowest limit reported in Trudu et al. (2023).

A comparison of our optical fluence limits with those obtained in previous works is shown in Figure 4.3, while we compare our optical-to-radio fluence ratio limits with previous works in Figure 4.4. We also compare our optical fluence and fluence ratio limits to previous works in Table 4.6.

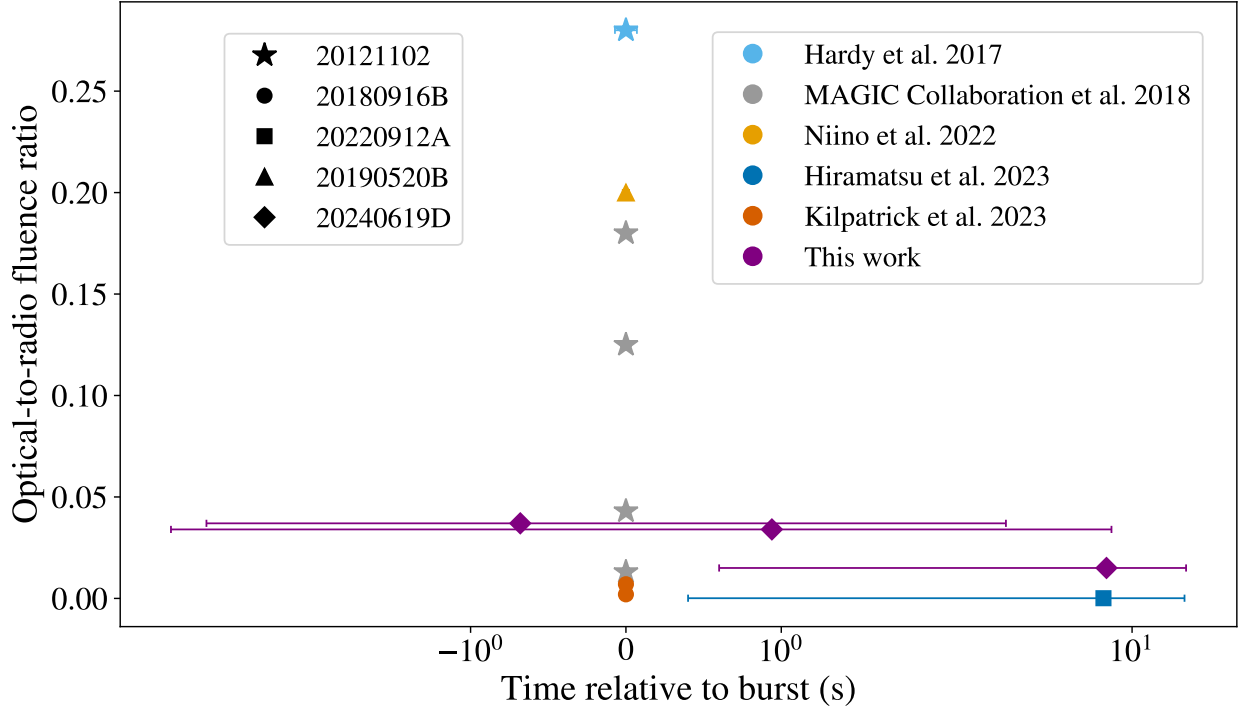


Figure 4.4: Optical-to-radio fluence ratio limits obtained by Hardy et al. (2017), the MAGIC Collaboration et al. (2018), Niino et al. (2022), Hiramatsu et al. (2023), and Kilpatrick et al. (2023), along with our deepest individual simultaneous, deepest summed simultaneous, and deepest individual non-simultaneous ratio limits for FRB 20240619D. The x-axis is linear near zero to display upper limits centered on the FRB arrival time, and then transitions to a logarithmic scale to accommodate larger timescales. We note once again that the lowest of our three limits shown here was calculated on a timescale of 0.6 s, and does not include the 15 s integration time of the image exposure. The same is true for the Hiramatsu et al. (2023) ratio limit, for which the optical fluence limit was calculated on a timescale of only 0.4 s, which is the delay between the burst TOA and the start of the optical exposure. The 15 s exposure length is not accounted for in their fluence limit.

Table 4.6: Fluence limits and fluence ratio limits for previous studies discussed, where available, along with the limits obtained for FRB 20240619D. The range of limits for the non-simultaneous bursts calculated on a timescale of just the delay time (“FD” in the table) are included, as well as limits for non-simultaneous bursts calculated on a timescale of the delay time added to the full integration time (“FDE” in the table). The range of limits for individual strictly simultaneous bursts, all calculated on a timescale of the full integration time (“FS” in the table), are also included, along with the range of strictly simultaneous limits obtained by averaging the fluence limits from the “on” images (“FSS” in the table). t_{radio} refers to the duration of the observed radio emission, and t_{opt} refers to the optical timescale.

Work	F_{opt} (Jy ms)	$F_{\text{opt}}/F_{\text{radio}}$	t_{radio} (ms)	t_{opt} (s)
Hardy et al. (2017)	$\lesssim 0.17$	$\lesssim 0.28$	$\sim 1.8 - 5.1$	0.1414
MAGIC Collaboration et al. (2018)	$\lesssim 0.025 - 0.36$	$\lesssim 0.013 - 0.18$	$\sim 1.2 - 5.7$	0.0001 – 0.01
Niino et al. (2022)	$\lesssim 0.029 - 0.34$	$\lesssim 0.20 - 2.1$	—	0.0409 – 2.1
Hiramatsu et al. (2023)	—	$\lesssim 0.00010 - 0.0010$	$\sim 0.01 - 300$	0.4 – 400
Kilpatrick et al. (2023)	—	$< 0.0020 - 0.0070$	2.7	0.0104
Trudu et al. (2023)	$\lesssim 0.0010 - 0.13$	—	$\sim 6 - 23$	0.2 – 30
This work (FD)	$\lesssim 0.040 - 14$	$\lesssim 0.015 - 16$	1.1 – 41.8	0.6 – 15.9
This work (FDE)	$\lesssim 0.91 - 27$	$\lesssim 0.11 - 36$	1.1 – 41.8	15.6 – 30.9
This work (FS)	$\lesssim 0.76 - 14$	$\lesssim 0.034 - 19$	2.7 – 41.8	15
This work (FSS)	$\lesssim 0.10 - 4.14$	$\lesssim 0.037 - 1.6$	2.7 – 41.8	8.4

Table 4.7: Details pertaining to individual bursts from FRB 20240619D. The L -band burst numbers are listed starting from 1 onwards, and then a number in brackets is shown, start from 70, because previous bursts were found in the L -band on earlier nights, for which we had no optical observations. Burst numbers that are “missing” are not shown because they were simultaneous across the UHF and L -band, and only the burst with the higher radio fluence is presented. “MK” in the table stands for MeerKAT and “ML” stands for MeerLICHT. Values of 0 in the delay time column mean that the burst was covered by a strictly simultaneous MeerLICHT observation. “FS” in the table stands for optical fluence limits where there was a strictly simultaneous optical observation. “FD” means the fluence limit for a non-simultaneous observation, where the timescale is just the delay time between the burst TOA and the start of the optical observation. “FDE” means the fluence limit for a non-simultaneous observation, where the timescale is the delay added to the full optical exposure time. Burst TOAs are topocentric at infinite frequency.

Burst no.	Burst TOA	F_{radio} (Jy ms)	ML t_{start}	Delay time (s)	Limiting mag (AB)	FS (Jy ms)	FD (Jy ms)	FDE (Jy ms)	ML Filter
UHF 1	60489.03202690	1.02	60489.032002	0	16.72	11.15	—	—	u
UHF 2	60489.04013016	2.10	60489.040090	0	19.63	0.76	—	—	q
UHF 4	60489.04061886	3.49	60489.040459	0	19.60	0.78	—	—	q
UHF 5	60489.04131341	1.65	60489.041184	0	19.60	0.79	—	—	q
UHF 6	60489.04131939	1.98	60489.041184	0	19.60	0.79	—	—	q
UHF 7	60489.04365003	3.87	60489.043821	14.8	18.82	—	1.60	3.22	i
UHF 8	60489.04778310	0.89	60489.047814	2.7	18.82	—	0.29	1.91	i
UHF 9	60489.04828085	3.72	60489.048175	0	18.77	1.69	—	—	i
UHF 10	60489.04974097	1.13	60489.049640	0	18.85	1.56	—	—	i
UHF 11	60489.05138845	0.72	60489.051537	12.9	19.58	—	0.69	1.48	q

Burst no.	Burst TOA	F_{radio} (Jy ms)	ML t_{start}	Delay time (s)	Limiting mag (AB)	FS (Jy ms)	FD (Jy ms)	FDE (Jy ms)	ML Filter
UHF 12	60489.05286051	0.84	60489.053005	12.5	19.53	—	0.70	1.54	<i>q</i>
UHF 13	60489.05286537	2.22	60489.053005	12.1	19.53	—	0.67	1.51	<i>q</i>
UHF 14	60489.05757381	3.76	60489.057404	0	19.56	0.82	—	—	<i>q</i>
UHF 15	60489.06320577	1.14	60489.063300	8.1	16.47	—	7.56	21.57	<i>u</i>
UHF 16	60489.06629332	1.92	60489.066286	0	19.52	0.85	—	—	<i>q</i>
UHF 17	60489.06693160	0.94	60489.067004	6.3	19.47	—	0.37	1.25	<i>q</i>
UHF 18	60489.06825268	0.87	60489.068122	0	19.50	0.86	—	—	<i>q</i>
UHF 20	60489.06883261	4.95	60489.068858	2.2	19.49	—	0.13	1.00	<i>q</i>
UHF 21	60489.06979846	0.90	60489.069955	13.5	19.47	—	0.80	1.69	<i>q</i>
UHF 22	60489.07038106	1.13	60489.070309	0	19.39	0.95	—	—	<i>q</i>
UHF 23	60489.07166943	1.98	60489.071765	8.3	19.46	—	0.50	1.39	<i>q</i>
UHF 24	60489.07189730	2.04	60489.071765	0	19.46	0.90	—	—	<i>q</i>
UHF 25	60489.07190416	1.03	60489.071765	0	19.46	0.90	—	—	<i>q</i>
UHF 26	60489.07249316	2.39	60489.072500	0.6	19.47	—	0.04	0.92	<i>q</i>
UHF 27	60489.07619613	2.60	60489.076240	3.8	18.76	—	0.43	2.13	<i>i</i>
UHF 28	60489.07836451	1.77	60489.078403	3.3	18.76	—	0.37	2.07	<i>i</i>
UHF 29	60489.08054537	3.16	60489.080708	14.1	19.44	—	0.85	1.76	<i>q</i>
UHF 30	60489.08054655	4.23	60489.080708	14.0	19.44	—	0.85	1.76	<i>q</i>
UHF 31	60489.08238328	1.33	60489.082542	13.7	19.44	—	0.83	1.74	<i>q</i>
UHF 32	60489.08398461	1.41	60489.084014	2.6	19.47	—	0.15	1.04	<i>q</i>
UHF 33	60489.08409388	4.56	60489.084014	0	19.47	0.89	—	—	<i>q</i>
UHF 34	60489.08409561	0.52	60489.084014	0	19.47	0.89	—	—	<i>q</i>
UHF 35	60489.08410538	2.18	60489.084014	0	19.47	0.89	—	—	<i>q</i>
UHF 36	60489.08416208	4.94	60489.084014	0	19.47	0.89	—	—	<i>q</i>
UHF 37	60489.08649998	2.20	60489.086560	5.2	19.50	—	0.30	1.16	<i>q</i>
UHF 38	60489.08931650	1.02	60489.089176	0	16.59	12.64	—	—	<i>u</i>
UHF 39	60489.09280853	1.45	60489.092841	2.8	16.55	—	2.44	15.54	<i>u</i>
UHF 40	60489.09574097	1.12	60489.095859	10.2	19.46	—	0.61	1.50	<i>q</i>
UHF 41	60489.10046762	1.92	60489.100590	10.6	19.42	—	0.66	1.59	<i>q</i>
UHF 44	60489.10606655	1.75	60489.106165	8.5	18.66	—	1.06	2.92	<i>i</i>
UHF 45	60489.10756602	2.84	60489.107630	5.6	18.69	—	0.68	2.50	<i>i</i>
UHF 46	60489.11245906	2.58	60489.112478	1.7	19.36	—	0.11	1.09	<i>q</i>
L 1 (70)	60489.03075755	2.16	60489.030901	12.4	16.72	—	9.20	20.35	<i>u</i>
L 2 (71)	60489.03138785	2.78	60489.031275	0	16.67	11.67	—	—	<i>u</i>
L 3 (72)	60489.03253289	2.77	60489.032367	0	16.67	11.70	—	—	<i>u</i>
L 4 (73)	60489.03266924	1.81	60489.032719	4.3	16.53	—	3.81	17.16	<i>u</i>
L 5 (74)	60489.03332576	0.58	60489.033465	12.0	16.69	—	9.22	20.74	<i>u</i>
L 6 (75)	60489.03642444	1.01	60489.036404	0	19.57	0.81	—	—	<i>q</i>
L 7 (76)	60489.03645382	1.25	60489.036404	0	19.57	0.81	—	—	<i>q</i>
L 8 (77)	60489.03654309	2.44	60489.036404	0	19.57	0.81	—	—	<i>q</i>
L 9 (78)	60489.03745971	1.02	60489.037523	5.4	19.63	—	0.28	1.04	<i>q</i>

Burst no.	Burst TOA	F_{radio} (Jy ms)	ML t_{start}	Delay time (s)	Limiting mag (AB)	FS (Jy ms)	FD (Jy ms)	FDE (Jy ms)	ML Filter
L 10 (79)	60489.03827492	6.56	60489.038251	0	19.63	0.77	—	—	<i>q</i>
L 11 (80)	60489.03983221	4.13	60489.039725	0	19.60	0.78	—	—	<i>q</i>
L 12 (81)	60489.04011458	0.91	60489.040090	0	19.63	0.76	—	—	<i>q</i>
L 13 (82)	60489.04053479	23.37	60489.040459	0	19.60	0.78	—	—	<i>q</i>
L 14 (83)	60489.04254167	1.19	60489.042652	9.5	19.63	—	0.48	1.25	<i>q</i>
L 15 (84)	60489.04257066	1.82	60489.042652	7.0	19.63	—	0.36	1.12	<i>q</i>
L 17 (86)	60489.04374908	0.93	60489.043821	6.2	18.82	—	0.67	2.30	<i>i</i>
L 18 (87)	60489.04528367	0.55	60489.045298	1.2	18.89	—	0.12	1.64	<i>i</i>
L 19 (88)	60489.04538562	1.49	60489.045298	0	18.89	1.51	—	—	<i>i</i>
L 20 (89)	60489.04542282	4.68	60489.045298	0	18.89	1.51	—	—	<i>i</i>
L 21 (90)	60489.04569712	2.02	60489.045666	0	18.87	1.54	—	—	<i>i</i>
L 22 (91)	60489.04583071	1.95	60489.045666	0	18.87	1.54	—	—	<i>i</i>
L 23 (92)	60489.04606793	1.76	60489.046019	0	18.83	1.59	—	—	<i>i</i>
L 24 (93)	60489.04616050	1.05	60489.046019	0	18.83	1.59	—	—	<i>i</i>
L 26 (95)	60489.05003469	0.75	60489.050001	0	18.78	1.67	—	—	<i>i</i>
L 27 (96)	60489.05045377	1.52	60489.050358	0	18.88	1.53	—	—	<i>i</i>
L 28 (97)	60489.05269545	1.49	60489.052650	0	19.56	0.82	—	—	<i>q</i>
L 29 (98)	60489.05407307	2.25	60489.054126	4.6	19.59	—	0.24	1.03	<i>i</i>
L 30 (99)	60489.05482668	1.79	60489.054858	2.7	19.51	—	0.15	1.01	<i>q</i>
L 31 (100)	60489.05552686	1.30	60489.055590	5.5	19.56	—	0.30	1.11	<i>q</i>
L 32 (101)	60489.05562429	2.99	60489.055590	0	19.56	0.81	—	—	<i>q</i>
L 33 (102)	60489.05683479	1.82	60489.056676	0	19.51	0.86	—	—	<i>q</i>
L 34 (103)	60489.05702569	1.54	60489.057049	2.0	19.55	—	0.11	0.94	<i>q</i>
L 35 (104)	60489.05721170	1.03	60489.057049	0	19.55	0.82	—	—	<i>q</i>
L 37 (106)	60489.05922397	1.36	60489.059288	5.5	16.58	—	4.65	17.34	<i>u</i>
L 38 (107)	60489.06010080	2.55	60489.060031	0	16.60	12.53	—	—	<i>u</i>
L 39 (108)	60489.06032269	0.93	60489.060405	7.1	16.63	—	5.78	17.96	<i>u</i>
L 40 (109)	60489.06100650	1.06	60489.061126	10.3	16.51	—	9.28	22.78	<i>u</i>
L 41 (110)	60489.06325794	1.51	60489.063300	3.6	16.47	—	3.35	17.36	<i>u</i>
L 42 (111)	60489.06420594	1.10	60489.064027	0	16.54	13.19	—	—	<i>u</i>
L 43 (112)	60489.06512695	4.55	60489.065109	0	16.59	12.57	—	—	<i>u</i>
L 44 (113)	60489.06584594	6.89	60489.065919	6.3	19.51	—	0.36	1.21	<i>q</i>
L 45 (114)	60489.06590736	1.10	60489.065919	1.0	19.51	—	0.06	0.91	<i>q</i>
L 46 (115)	60489.06613799	5.80	60489.066286	12.8	19.52	—	0.72	1.57	<i>q</i>
L 47 (116)	60489.06811170	2.47	60489.068122	0.9	19.50	—	0.05	0.91	<i>q</i>
L 48 (117)	60489.06876437	4.73	60489.068858	8.1	19.49	—	0.47	1.34	<i>q</i>
L 49 (118)	60489.06883027	9.18	60489.068858	2.4	19.49	—	0.14	1.01	<i>q</i>
L 50 (119)	60489.06892518	2.01	60489.068858	0	19.49	0.87	—	—	<i>q</i>
L 51 (120)	60489.06902822	0.89	60489.068858	0	19.49	0.87	—	—	<i>q</i>
L 52 (121)	60489.06964073	4.14	60489.069593	0	19.39	0.95	—	—	<i>q</i>
L 53 (122)	60489.06976985	0.78	60489.069593	0	19.39	0.95	—	—	<i>q</i>

Burst no.	Burst TOA	F_{radio} (Jy ms)	ML t_{start}	Delay time (s)	Limiting mag (AB)	FS (Jy ms)	FD (Jy ms)	FDE (Jy ms)	ML Filter
L 54 (123)	60489.07012541	3.33	60489.069955	0	19.47	0.89	—	—	<i>q</i>
L 56 (125)	60489.07171468	1.44	60489.071765	4.4	19.46	—	0.26	1.16	<i>q</i>
L 57 (126)	60489.07184715	1.69	60489.071765	0	19.46	0.90	—	—	<i>q</i>
L 58 (127)	60489.07249166	2.87	60489.072500	0.7	19.47	—	0.04	0.93	<i>q</i>
L 59 (128)	60489.07292448	1.61	60489.072972	4.1	18.77	—	0.46	2.16	<i>i</i>
L 60 (129)	60489.07364477	1.10	60489.073689	3.8	18.79	—	0.42	2.08	<i>i</i>
L 61 (130)	60489.07495680	0.88	60489.074777	0	18.76	1.71	—	—	<i>i</i>
L 62 (131)	60489.07540227	1.00	60489.075507	9.1	18.82	—	0.97	2.59	<i>i</i>
L 63 (132)	60489.07551338	1.34	60489.075507	0	18.82	1.61	—	—	<i>i</i>
L 64 (133)	60489.07589325	3.13	60489.075874	0	18.68	1.84	—	—	<i>i</i>
L 65 (134)	60489.07627033	5.80	60489.076240	0	18.76	1.70	—	—	<i>i</i>
L 66 (135)	60489.07643545	2.01	60489.076603	14.5	18.80	—	1.59	3.23	<i>i</i>
L 67 (136)	60489.07723522	0.74	60489.077337	8.8	18.72	—	1.03	2.80	<i>i</i>
L 68 (137)	60489.07815854	1.30	60489.078052	0	18.70	1.80	—	—	<i>i</i>
L 70 (139)	60489.07887732	1.58	60489.078777	0	18.78	1.68	—	—	<i>i</i>
L 72 (141)	60489.08079254	2.02	60489.080708	0	19.44	0.91	—	—	<i>q</i>
L 73 (142)	60489.08081744	0.96	60489.080708	0	19.44	0.91	—	—	<i>q</i>
L 74 (143)	60489.08184327	0.82	60489.081814	0	19.41	0.93	—	—	<i>q</i>
L 75 (144)	60489.08197116	2.30	60489.081814	0	19.41	0.93	—	—	<i>q</i>
L 76 (145)	60489.08201452	2.94	60489.082176	14.0	19.45	—	0.84	1.74	<i>q</i>
L 77 (146)	60489.08300774	0.88	60489.082915	0	19.46	0.89	—	—	<i>q</i>
L 79 (148)	60489.08520675	1.44	60489.085092	0	19.48	0.88	—	—	<i>q</i>
L 80 (149)	60489.08582868	1.16	60489.085827	0	19.42	0.93	—	—	<i>q</i>
L 81 (150)	60489.08631557	1.02	60489.086208	0	19.50	0.87	—	—	<i>q</i>
L 82 (151)	60489.09087863	5.53	60489.091013	11.6	16.50	—	10.57	24.21	<i>u</i>
L 83 (152)	60489.09111509	1.29	60489.091013	0	16.50	13.64	—	—	<i>u</i>
L 84 (153)	60489.09265684	2.04	60489.092841	15.9	16.55	—	13.89	26.99	<i>u</i>
L 85 (154)	60489.09353941	1.33	60489.093577	3.3	16.45	—	3.11	17.42	<i>u</i>
L 86 (155)	60489.09410937	8.08	60489.093958	0	16.49	13.84	—	—	<i>u</i>
L 87 (156)	60489.09462207	2.50	60489.094698	6.5	16.51	—	5.92	19.48	<i>u</i>
L 88 (157)	60489.09477181	0.70	60489.094698	0	16.51	13.56	—	—	<i>u</i>
L 89 (158)	60489.09527421	0.68	60489.095139	0	19.44	0.91	—	—	<i>q</i>
L 90 (159)	60489.09572763	1.45	60489.095859	11.3	19.46	—	0.67	1.57	<i>q</i>
L 91 (160)	60489.09587468	0.74	60489.095859	0	19.46	0.89	—	—	<i>q</i>
L 92 (161)	60489.09853510	4.52	60489.098419	0	19.42	0.93	—	—	<i>q</i>
L 93 (162)	60489.09881034	6.07	60489.098777	0	19.43	0.92	—	—	<i>q</i>
L 94 (163)	60489.09885696	2.62	60489.098777	0	19.43	0.92	—	—	<i>q</i>
L 95 (164)	60489.09990707	2.81	60489.099863	0	19.37	0.97	—	—	<i>q</i>
L 96 (165)	60489.10142470	4.82	60489.101311	0	19.39	0.96	—	—	<i>q</i>
L 97 (166)	60489.10210758	3.27	60489.102044	0	19.38	0.97	—	—	<i>q</i>
L 98 (167)	60489.10221868	1.39	60489.102044	0	19.38	0.97	—	—	<i>q</i>

Burst no.	Burst TOA	F_{radio} (Jy ms)	ML t_{start}	Delay time (s)	Limiting mag (AB)	FS (Jy ms)	FD (Jy ms)	FDE (Jy ms)	ML Filter
L 99 (168)	60489.10380253	3.18	60489.103642	0	18.71	1.79	—	—	<i>i</i>
L 100 (169)	60489.10509503	1.46	60489.105079	0	18.54	2.09	—	—	<i>i</i>
L 101 (170)	60489.10589710	1.42	60489.105799	0	18.64	1.91	—	—	<i>i</i>
L 102 (171)	60489.10703360	3.19	60489.106896	0	18.72	1.76	—	—	<i>i</i>
L 103 (172)	60489.10740734	1.87	60489.107267	0	18.71	1.79	—	—	<i>i</i>
L 104 (173)	60489.10825775	1.86	60489.108374	10.1	18.67	—	1.25	3.10	<i>i</i>
L 105 (174)	60489.10842341	3.07	60489.108374	0	18.67	1.85	—	—	<i>i</i>
L 106 (175)	60489.11207605	2.12	60489.112122	4.0	19.38	—	0.25	1.21	<i>q</i>
L 107 (176)	60489.11235771	0.64	60489.112478	10.4	19.36	—	0.68	1.66	<i>q</i>

4.6 Conclusions and future analysis

For the repeating FRB 20240619D, we managed to obtain strictly simultaneous MeerLICHT optical observations for 80 out of the 142 radio bursts that were detected on 2024 June 28. Although we detected no optical counterpart to any of the bursts, we set upper limits on the optical fluence as deep as 0.04 Jy ms for a burst where we had an optical observation that started ~ 0.6 s after the arrival time of the burst, and where we just use the 0.6 s delay time as the fluence timescale, and 0.76 Jy ms for a burst where we had a strictly simultaneous optical observation of 15 s duration. We also calculated a summed and averaged strictly simultaneous optical fluence limit of 0.10 Jy ms from our *q*-band “on” image.

The FD of 0.04 Jy ms we obtained is deeper than some limits in previous works, as is its associated optical-to-radio fluence ratio limit of $\lesssim 0.015$. Our deepest FS, on the other hand, was not as deep as any of the other works considered, due to our timescale of 15 s, which is very long compared to the timescales used in other studies. Additionally, if we rather calculate fluence limits for non-simultaneous bursts on timescales of the delay time added to the full integration time, then our FDE of 0.91 Jy ms is also not as deep as any of the previous works mentioned. Nevertheless, our deepest strictly simultaneous optical-to-radio fluence ratio limit of $\lesssim 0.034$ is deeper than some previously set limits. Our FSS of 0.10 Jy ms was comparable to strictly simultaneous optical fluence limits obtained in previous works, and was deeper than some previous limits. Although we do discuss our FD of 0.04 Jy ms, our preference is to prioritise our deepest strictly simultaneous optical fluence limit for an individual burst, our summed and averaged strictly simultaneous optical fluence limit, and our deepest non-simultaneous fluence limit for an individual burst that was calculated using the delay time added to the integration time, as we are of the belief that it is important for the optical fluence limits pertaining to FRBs to include the optical integration time, as opposed to just using the delay time in situations where there is no strictly simultaneous optical observation of a burst.

At the time of writing, the host galaxy and redshift of FRB 20240619D have not yet been determined, meaning that we are not yet able to estimate the radio and optical energies and luminosities of the bursts. When we are able to estimate these values, we will be able to compare these intrinsic properties of the bursts to those of other FRBs, and we will also be able to compare our optical limits to the synchrotron maser model, as we did for FRB 20230808F in Section 3.5.2, which could potentially provide constraints on the model. The results of the optical analysis of FRB 20240619D are part of a publication by Tian et al., which has been

accepted for publication in the Monthly Notices of the Royal Astronomical Society (Tian et al., 2025).

Chapter 5

Conclusions and recommendations for future work

We have reported on the optical analysis, using MeerLICHT, of two new FRBs, both discovered by MeerKAT. One of these is the non-repeating FRB 20230808F, while the other is the repeating FRB 20240619D, which is also the first ever repeating FRB to be discovered with MeerKAT.

For FRB 20230808F, we obtained an optical exposure with MeerLICHT that started approximated 3.4 seconds after the arrival time of the burst. This represents the shortest time delay between radio and optical observations of a non-repeating FRB. We were able to localise the FRB using MeerTRAP’s transient buffer pipeline, and, with spectroscopic SALT observations, we were able to determine a host galaxy redshift of $z = 0.3472 \pm 0.0002$ for the FRB. We also determined the dispersion measure of the FRB to be $DM = 653.2 \pm 0.4 \text{ pc cm}^{-3}$ and a rotation measure $RM = 169.4 \pm 0.2 \text{ rad m}^{-2}$, and the radio fluence $F_{\text{radio}} = 1.72 \pm 0.01 \text{ Jy ms}$. From the MeerLICHT image obtained $\sim 3.4 \text{ s}$ after the FRB, we calculated an optical flux limit of $11.7 \mu\text{Jy}$, corresponding to optical fluence limits of 0.039 Jy ms on a timescale of $\sim 3.4 \text{ s}$, and 0.74 Jy ms on a timescale of $\sim 63.4 \text{ s}$. Since we had a redshift estimate, we were also able to estimate the optical luminosity limit, and obtained $\nu L_\nu \sim 1.3 \times 10^{43} \text{ erg s}^{-1}$.

For FRB 20240619D, we obtained MeerLICHT and MeerKAT observations on 2024 June 28. Out of the 142 unique bursts detected by MeerKAT on this date, we obtained strictly simultaneous optical coverage for 80. The other 62 bursts were detected during MeerLICHT’s overhead time. We were able to calculate fluence upper limits under several conditions: we calculated upper limits for bursts with strictly simultaneous optical coverage on the timescale of the optical integration time, which is 15 s (which we refer to as “FS”). We calculated upper limits for bursts without strictly simultaneous optical coverage on two timescales: using only the delay time between the burst arrival time and the start of the optical exposure as the timescale (“FD”), and using the delay time added to the full optical integration time of 15 s as the timescale (“FDE”). Of these two timescales, we favour the method that includes the integration time, as this is consistent with how we calculated the strictly simultaneous limits. Lastly, we calculated summed and averaged strictly simultaneous optical fluence limits (“FSS”) from the co-adds that we generated using all of the MeerLICHT images that contained burst arrival times. Our deepest FS was 0.76 Jy ms , our deepest FDE was 0.91 Jy ms , our deepest FD was 0.04 Jy ms , and our deepest FSS was 0.10 Jy ms . Although our deepest FD was also our deepest fluence limit overall, we still favour our other limits more. Compared to previous works, our optical fluence upper limits tended to not be as deep, due to the long timescales that we had to consider for our fluence calculations.

We did not detect an optical counterpart for either of the FRBs discussed in this thesis, and nor were we able to place constraints on any emission models. However, we were able to determine that, for FRB 20230808F, if it had been at a redshift of $z \lesssim 0.15$, and our flux limits were the same, then our limits would have constrained the synchrotron maser model (Margalit et al., 2020; Cooper et al., 2022). Conversely, we can also estimate that, if the redshift of $z \sim 0.347$ remained the same, but the flux limits obtained were approximately 10 times deeper, they could also have constrained the model.

We are also able to make recommendations for future work in the area of searching for an optical counterpart to FRBs.

One of the pros of our observing strategy is the fact that, when MeerLICHT and MeerKAT are synced, every second MeerLICHT exposure is a q -band exposure. As the q -band is the deepest of the MeerLICHT filters, this is beneficial for us in setting deep upper limits for any optical emission that could be associated with FRBs.

One difficulty we encountered with our observing strategy, which is mentioned in Section 2.3, was the fact that MeerLICHT could not sync with MeerKAT, even if most conditions were favourable, if MeerLICHT's HA limit would be surpassed at any point during the scheduled MeerKAT observing block. In cases where the HA limit will be surpassed later in the observing block, it would perhaps be beneficial for syncing to be established, at least for part of the block, and for the connection to later be suspended once the HA limit is being approached.

MeerLICHT's general observing strategy of 1-minute exposures in a filter sequence where the filter changes in between each exposure, means that we have an overhead time of approximately 15-25s between exposures. This corresponds to around 30 per cent of MeerLICHT's observation time being composed of overhead time, which, following Ofek & Ben-Ami (2020), is ideal. However, it is not the most efficient strategy for trying to obtain simultaneous optical-radio observations of FRBs, simply because 1-minute exposures are too long for trying to set upper limits on very short timescales for FRBs. This becomes apparent when, for example, we calculate fluence limits on a timescale equal to the exposure length and obtain relatively shallow limits due to our long exposure times. However, due to the fact that MeerLICHT uses a CCD, the readout time will always be slower than if we were using a CMOS sensor. For future work on searching for optical emission associated with FRBs, it might be more appropriate to use telescopes equipped with CMOS sensors. One possible upcoming project that could be better suited to searching for FRBs in this regard is *Flash*, which is an upcoming optical telescope being developed at the University of Cape Town. It will have a CMOS sensor, and will be able to take exposures with integration times shorter than 0.1s, making it better suited to the task of searching for optical counterparts to FRBs.

Acknowledgements pertaining to Chapter 3

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