Limits on Simultaneous and Delayed Optical Emission from Well-localized Fast Radio Bursts

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ABSTRACT

We present the largest compilation to date of optical observations during and following fast radio bursts (FRBs). The data set includes our dedicated simultaneous and follow-up observations, as well as serendipitous archival survey observations, for a sample of 15 well-localized FRBs: eight repeating and seven one-off sources. Our simultaneous (and nearly simultaneous with a 0.4 s delay) optical observations of 13 (1) bursts from the repeating FRB 20220912A provide the deepest such limits to date for any extragalactic FRB, reaching a luminosity limit of $\nu L_\nu \lesssim 10^{42}$ erg s$^{-1}$ ($\lesssim 2 \times 10^{41}$ erg s$^{-1}$) with 15–400 s exposures; an optical-flux-to-radio-fluence ratio of $f_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-7}$ ms$^{-1}$ ($\lesssim 10^{-8}$ ms$^{-1}$); and flux ratio of $f_{\text{opt}}/f_{\text{radio}} \lesssim 0.02$–$2 \times 10^{-5}$ ($\lesssim 10^{-6}$) on millisecond to second timescales. These simultaneous limits provide useful constraints in the context of FRB emission models, such as the pulsar magnetosphere and pulsar nebula models. Interpreting all available optical limits in the context of the synchrotron maser model, we find that they constrain the flare energies to $\lesssim 10^{44}$–$10^{49}$ erg (depending on the distances of the various repeating FRBs, with $\lesssim 10^{43}$ erg for the Galactic SGR 1935+2154). These limits are generally at least an order of magnitude larger than those inferred from the FRBs themselves, although in the case of FRB 20220912A our simultaneous and rapid follow-up observations severely restrict the model parameter space. We conclude by exploring the potential of future simultaneous and rapid-response observations with large optical telescopes.

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1. INTRODUCTION

Fast radio bursts (FRBs) are incredibly bright, millisecond-duration pulses at GHz frequencies (e.g., Lorimer et al. 2007; see Petroff et al. 2019, 2022 for reviews). Their dispersion measures (DMs), the integrated electron column density along the line of sight, exceed the range of the Milky Way (MW) plus its halo, implying an extragalactic origin. While most FRBs appear as one-off events, a growing subset are known to repeat (e.g., Spitler et al. 2016; see CHIME/FRB Collaboration et al. 2019 and Fonseca et al. 2020 for sample studies), and it is possible that the entire population repeats on a wide range of timescales (e.g., Nicholl et al. 2017; Ravi 2019; Cui et al. 2021). To date, about 20 FRBs (both one-off and repeaters) have been precisely localized through their radio emission, providing an initial, though potentially biased, view of their host-galaxy environments (see, e.g., Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017; see further Heintz et al. 2020; Bhandari et al. 2022), and directly confirming their extragalactic origin.

Despite the rapidly increasing sample size and the availability of some localizations and host-galaxy properties, the physical origin(s) and mechanism(s) of FRBs remain unknown, with dozens of proposed sources and emission mechanisms published to date (see, e.g., Platts et al. 2019 for a living list of theoretical FRB models).\(^1\) Given the short duration and noncatastrophic nature of the repeating FRBs, models involving young neutron stars or black holes are particularly popular; the recent faint FRB-like detection from the Galactic magnetar SGR 1935+2154 may support such a picture (CHIME/FRB Collaboration et al. 2020a; Bochenek et al. 2020). Some of the precisely localized extragalactic FRBs (e.g., FRB 20200120E in an M81 globular cluster; Bhardwaj et al. 2021; Kirsten et al. 2022 a) show no correlation with star formation, possibly indicating an origin from older neutron stars, accretion-powered binaries (e.g., Sridhar et al. 2021), or from young magnetars born from an older progenitor channel (e.g., accretion-induced collapse of white dwarfs or the merger of two neutron stars; Margalit et al. 2019; Kremer et al. 2022).

A significant barrier to our understanding of FRBs is their sole detection in the radio band (see, e.g., Chen et al. 2020; Nicastro et al. 2021 for reviews on multi-wavelength observations).\(^2\) This situation is reminiscent of the first two decades of gamma-ray burst (GRB) research when only gamma-ray emission had been detected; it was only through rapid multiwavelength detections of associated afterglows that the progenitors and physics of GRBs were eventually uncovered.\(^3\)

In the same vein, rapid and deep optical follow-up of FRBs may shed light on their physical mechanisms. FRB models predict a wide range of possible luminosities and timescales for optical transient counterparts, ranging from no emission at all, to luminous ($\gtrsim 10^{44} \text{ erg s}^{-1}$) afterglows on a millisecond timescale, to fainter ($\lesssim 10^{39} \text{ erg s}^{-1}$) afterglows on timescales of minutes to hours (e.g., Lyubarsky 2014; Beloborodov 2017; Metzger et al. 2019; Yang et al. 2019; Margalit et al. 2020a,b; Beloborodov 2020). Previous optical follow-up attempts have suffered from the combination of FRB poor localizations, large distances, delayed announcements of bursts, and a limited sample of repeating FRBs, resulting in only weak constraints (e.g., $\lesssim 10^{45} \text{ erg s}^{-1}$ over a millisecond timescale to $\lesssim 10^{43} \text{ erg s}^{-1}$ over a minute timescale; Hardy et al. 2017; MAGIC Collaboration et al. 2018; Andreoni et al. 2020; Niino et al. 2022); dedicated monitoring of a single burst from the well-localized repeating FRB 20180916B ($d_L \approx 150 \text{ Mpc}$; Marcote et al. 2020) placed marginal constraints ($\lesssim 10^{40} \text{ erg s}^{-1}$ over minute timescale) on models such as the synchrotron maser with high burst energies and circumburst densities (Kilpatrick et al. 2021).

Here, we report the largest set of optical constraints to date, for a sample of eight well-localized repeating FRBs (including the Galactic SGR 1935+2154) and seven well-localized non-repeating FRBs, using an extensive set of archival data, as well as our own dedicated follow-up observations of the nearby repeating FRB 20200120E, and simultaneous observations of the...

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\(^1\) https://frbtheorycat.org/index.php/Main_Page

\(^2\) Temporally coincident X-ray bursts from the Galactic SGR 1935+2154 (Mereghetti et al. 2020; Li et al. 2021a; Ridnaia et al. 2021; Tavani et al. 2021) remain the only non-radio transient detections. However, such bursts would not be detectable in extragalactic FRBs due to their much larger distances (see e.g., Scholz et al. 2016, 2017, 2020; Tavani et al. 2020 for X-ray nondetections of extragalactic FRBs).

\(^3\) A key distinction is that for GRBs detections of afterglows at longer wavelengths were critical for precise localizations and the identification of host galaxies (and hence a distance scale and stellar population properties), whereas FRBs can be precisely localized directly in the radio band.
newly discovered and highly active FRB 20220912A (McKinven & CHIME/FRB Collaboration 2022), the most sensitive simultaneous observations to date for any extragalactic FRB. The paper is structured as follows. We summarize the FRB sample, optical observations, and data reduction in Section 2. In Section 3, we analyze and discuss the optical luminosity, flux, and fluence limits in the context of the FRBs’ radio properties, and compare these to theoretical models. We summarize our findings and conclude with a future outlook in Section 4.

2. SAMPLE AND OBSERVATIONS

2.1. Fast Radio Burst Sample

We select a sample of FRBs that are well localized ($\lesssim 2''$) and with known host-galaxy identifications, located at decl. $\gtrsim -30^\circ$ in order to have access to the radio burst measurements from the Canadian Hydrogen Intensity Mapping Experiment/FRB (CHIME/FRB Collaboration et al. 2018) Public Database and optical forced photometry from the Zwicky Transient Facility (ZTF; Bellm et al. 2019; Graham et al. 2019) and Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2020) Public Database. We also include any other radio and optical data sets from the literature. We select both repeating and non-repeating FRBs; however, we find that all of the optical limits for non-repeating FRBs are not particularly constraining given the small number of bursts and large distances (see Appendix A). Therefore, we focus on the repeating FRBs in the subsequent analysis. Their properties and references are summarized in Table 1. We note that the distance to the Galactic SGR 1935+2154 is not well constrained, which also results in a large extinction uncertainty.

2.2. Optical Observations

For each FRB in our sample, we obtained optical photometry from the ZTF forced-photometry service (Masci et al. 2019) in the $g$, $r$, and $i$ bands, and the ATLAS forced photometry server (Shingles et al. 2021) in the $c$ and $o$ bands for the entire time interval spanning all of the radio bursts for each FRB (i.e., from the first to last measured bursts). The detection significance ($\sigma$) of optical measurements was determined from the ratio of measured flux ($f$) to its error ($f_{err}$). For any measurements above $3\sigma$, we visually inspected the difference images and found that all were due to subtraction artifacts (e.g., bad focus, world coordinate system offset, shutter problems). Thus, we calculate the $3\sigma$ upper limits as $-2.5\log_{10}(3 \times f_{err}) + ZP$, where “ZP” is the zero point in the AB magnitude system.

In addition, we carried out dedicated monitoring observations of the nearby FRB 20200120E in M81 (Bhardwaj et al. 2021; Kirsten et al. 2022a) with 300 s exposures simultaneously in the $g$, $r$, $i$, and $z$ bands from 2021 March 19 to 2022 May 18 (UT dates are used throughout) roughly every 10 days with MuSCAT3 (Narita et al. 2020) on the 2 m Faulkes Telescope North (Hawaii, USA) in the Las Cumbres Observatory (LCO; Brown et al. 2013) network. These images have typical $griz$-band $3\sigma$ limiting magnitudes of 22.8, 22.9, 22.3, and 22.0, respectively. The March 19 observations, during which no FRBs were announced, were used as template images, and image subtraction was performed using lcogtsnpipe (Valenti et al. 2016), a PyRAF-based photometric reduction pipeline, and PyZOGY (Guevel & Hosseinzadeh 2017), an implementation in Python of the subtraction algorithm described in Zackay et al. (2016). The $griz$-band data were calibrated to AB magnitudes using the 13th Data Release of the Sloan Digital Sky Survey (SDSS; Albareti et al. 2017). For the recently discovered highly active FRB 20220912A (McKinven & CHIME/FRB Collaboration 2022), we carried out monitoring observations during the CHIME observing windows with three facilities: a series of 40 s exposures and a series of 60 s exposures in the $r$ band with KeplerCam (Szentgyorgyi et al. 2005) on the 1.2 m Telescope at the Fred Lawrence Whipple Observatory (FLWO; Arizona, USA), reaching typical $3\sigma$ limiting magnitudes of 20.5 and 21.1, respectively; a series of 400 s exposures in the $r$ band with the Sinistro camera on the 1 m telescope at the McDonald Observatory (Texas, USA) in the LCO network, reaching a typical $3\sigma$ limiting magnitude of 22.6; and a series of 15 s exposures in the $r$ band with Binospec (Fabricant et al. 2019) on the 6.5 m MMT Observatory (Arizona, USA), reaching a typical $3\sigma$ limiting magnitude of 23.2. In total, we obtained 10 simultaneous optical observations during 13 FRB detections: nine with KeplerCam.

4 See https://frbhosts.org for the up-to-date list of FRB host-galaxy identifications
5 https://www.chime-frb.ca/
6 Typical ZTF and ATLAS PSF FWHMs are $2''$ and $4''$, respectively, comparable to and larger than the adopted FRB localization error limit.
7 https://ztfweb.ipac.caltech.edu/cgi-bin/request ForcedPhotometry.cgi
8 https://fallingstar-data.com/forcedphot/
9 https://github.com/LCOGT/lcogtsnpipe
10 https://github.com/dguevel/PyZOGY
11 https://www.chime-frb.ca/astronomytools
12 One of which was reported in Hiramatsu et al. (2022).
Data sources: CHIME (CHIME/FRB Public Database; CHIME/FRB Collaboration et al. 2019, 2020b; Pleunis et al. 2021), Apertif (Pastor-Marazuela et al. 2021), Effelsberg (Hilmarsson et al. 2021a), DSN (Majid et al. 2020; Pearlman et al. 2020), CHIME (Josephy et al. 2021), Onsala (Kirsten et al. 2021 b), Parks (Kumar et al. 2022), Stockert (Herrmann 2021), Usuda Deep Space Center (UDSC; Takefuji et al. 2022; Ikebe et al. 2023), uGMRT (Marthi et al. 2020; Pleunis et al. 2021; Sand et al. 2022), Very Large Array (VLA; Aggarwal & Realfast Collaboration 2020; Aggarwal et al. 2020).

*Only the bursts with reported time of arrival are included.
*b Calculated from the host redshift assuming a Lambda cold dark matter (ΛCDM) cosmology with \( H_0 = 71.0 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_L = 0.7 \), and \( \Omega_m = 0.3 \), unless otherwise noted.
*c Only the bursts with reported time of arrival are included.
*d If only two of the width (\( \tau_{\text{FRB}} \)), flux (\( F_{\text{radio}} \)), and fluence (\( F_{\text{radio}} \)) are reported for a particular burst, the third parameter is estimated assuming \( F_{\text{radio}} \sim F_{\text{radio}}^{-\tau_{\text{FRB}}} \).
*e Best localized with the European VLBI Network (EVN; Kirsten et al. 2022a).
*f From Speights & Westpfahl (2012), retrieved via the NASA/IPAC Extragalactic Database.

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**e Best localized with the European VLBI Network (EVN; Kirsten et al. 2022a).
**f From Speights & Westpfahl (2012), retrieved via the NASA/IPAC Extragalactic Database.

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### Table 1. The Sample of Well-localized Repeating FRBs

| FRB      | R.A.        | Decl.       | Redshift | \( d_L \) | \( d_M \) | \( A_{V,\text{MW}} \) | Events | Frequency | DM | Width | Flux | Fluence |
|----------|-------------|-------------|----------|----------|---------|-------------------|--------|------------|----|-------|------|---------|
| 20200120B | 149.4779140(3) \( ^{f} \) | +68.8169036(4) \( ^{f} \) | -0.00113 \( ^{f} \) | 3.6 \( ^{f} \) | 0.200 | 74 \( ^{g} \) | 0.40-2.3 | 87.7-88 | 0.014-0.70 | 0.10-60 | 0.04-2 |
| 20180916B | 29.5031257(6) \( ^{h} \) | +65.7167542(6) \( ^{h} \) | 0.0337 \( ^{h} \) | 149 \( ^{h} \) | 2.712 | 244 \( ^{i} \) | 0.12-4.9 | 343-356 | 0.13-158 | 0.12-20 | 0.08-300 |
| 20220912A | 347.2704(6) \( ^{d} \) | +48.7071(3) \( ^{d} \) | 0.77 \( ^{d} \) | 344 | 0.637 | 72 \( ^{k} \) | 0.11-2.3 | 218-228 | 0.8-300 | 3-290 | 1.5-900 |
| 20211124A | 77.0146142(8) \( ^{l} \) | +26.6066997(9) \( ^{l} \) | 0.0979 \( ^{l} \) | 444 | 1.964 | 2914 \( ^{m} \) | 0.40-2.3 | 409-424 | 0.9-300 | 0.004-220 | 0.005-770 |
| 20221012A | 82.994575(4) \( ^{n} \) | +33.147940(1) \( ^{n} \) | 0.1927 \( ^{n} \) | 927 | 2.098 | 3658 \( ^{o} \) | 0.60-7.5 | 527-698 | 0.01-78.52 | 0.002-70 | 0.002-35 |
| 20220720B | 240.51780(3) \( ^{p} \) | -11.28814(2) \( ^{p} \) | 0.241 \( ^{p} \) | 1192 | 0.769 | 230 \( ^{q} \) | 1.46-6.2 | 1164-1291 | 0.7-33.1 | 0.002-9 | 0.029-6 |
| 20180801A | 93.2268(2) \( ^{r} \) | +6.4711(2) \( ^{r} \) | 0.3304 \( ^{r} \) | 1712 | 1.231 | 510-536 | 1.2-1.3 | 17-123 | 1.05-2 | 0.021-4.90 |

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### Table 2. Missing Text

| SGR               | \( d_L \) | \( d_M \) | \( A_{V,\text{MW}} \) | Events | Frequency | DM | Width | Flux | Fluence |
|-------------------|----------|---------|-------------------|--------|------------|----|-------|------|---------|
| 1935+2514         | 293.7317(2) \( ^{l} \) | +21.8966(2) \( ^{l} \) | Galactic \( ^{l} \) | 9.0 \( ^{u} \) | 7.2 \( ^{v} \) | 14 \( ^{w} \) | 0.11-5.6 | 313-333 | 0.22-2000 | 0.030-2.5 \( \times 10 \) | 0.06-1.5 \( \times 10 \) |

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The table above lists various FRBs with their respective properties, including redshifts, distances, and other relevant data. The notes indicate the sources of the data and provide additional context for understanding the table.
Figure 1. Top: schematic timeline of the KeplerCam and LCO simultaneous exposures, as well as the temporally closest MMT/Binospec exposure with respect to the FRB 20220912A bursts detected by CHIME and DSA (where \( N \) is the number of bursts detected within 1 s), color-coded by the observed \( r \)-band limiting magnitude. The UT date labeled next to each point is its exposure start time. In total, we covered 13 bursts in 10 simultaneous exposures: one DSA detection each in two KeplerCam exposures, one CHIME detection each in five KeplerCam exposures, and two CHIME detections each in two KeplerCam and one LCO exposures. Bottom: simultaneous KeplerCam 60 s image during the two CHIME detections (left), the corresponding PS1 template image (middle), and the resulting difference image (right), with the DSA localization region and host galaxy marked by the magenta ellipse (\( \Delta R.A. \sim 2'' \) & \( \Delta \text{decl.} \sim 1'' \); Ravi et al. 2022a) and navy circle (Kron radius = 3.44 from PS1 DR2; Flewelling et al. 2020), respectively. No optical counterpart is identified down to a \( r \)-band limiting magnitude of 21.1.
for the two Deep Synoptic Array (DSA) detections on 2022 October 18 and 25 (Ravi et al. 2022a) and the nine CHIME detections on October 20, 25, and 30 and November 7 and 9 (CHIME VOEvent Service13); and one with LCO for the two CHIME detections on October 22. These KeplerCam and LCO simultaneous exposures, as well as a nearly simultaneous Binospec exposure 0.4 s after a CHIME detection, are shown in Figure 1. Due to the uncertainty (≪ a few seconds) in the shutter opening time stamps (from the open command being issued to the shutter being fully opened), the nearly simultaneous Binospec exposure may indeed be simultaneous. We note this caveat in the following analysis and discussion wherever appropriate.

Using a custom photometry pipeline, the KeplerCam, LCO, and Binospec data were reduced and calibrated to AB magnitudes from the Pan-STARRS1 (PS1; Chambers et al. 2016) Data Release 2 (DR2; Flewelling et al. 2020). Cosmic rays were identified and masked using Cosmic–CONN15 (Xu et al. 2021a,b, 2022a), and image subtraction was performed against PS1 template images using PyZOGY. For each simultaneous exposure, we stacked it with the subsequent exposures in the same series to obtain deeper limits (typical limiting magnitudes of 21.5 and 23 for KeplerCam and LCO observations, respectively). An example image subtraction is shown in Figure 1 for one of the simultaneous KeplerCam images. We do not detect any transient source in the subtracted KeplerCam, LCO, and Binospec images within any of the FRB localization regions. Thus, we report their 3σ upper limits.

We correct all optical limits for the MW extinction assuming the Fitzpatrick (1999) reddening law with RV = 3.1. After correcting the DM- and frequency-dependent time delay (see Equation (1) of Cordes & Chatterjee 2019) and referencing all the radio and optical measurements to the solar system barycenter (Eastman et al. 2010),16 we find the temporally closest radio burst for each optical limit with respect to the optical exposure midpoint to determine the time difference.

3. ANALYSIS AND DISCUSSION

3.1. Optical Luminosity Limits

None of our simultaneous and follow-up observations or the archival observations have led to a detected optical counterpart. We plot all of the resulting KeplerCam, LCO, and Binospec luminosity limits, along with the archival and literature sample in Figure 2. Most of the untargeted ZTF and ATLAS observations occur ≳ 10^4 s before and/or after radio bursts, with a wide luminosity limit range of ~ 10^{35–45} erg s^-1; the deepest limits are for the Galactic magnetar SGR 1935+2154, given the much smaller distance compared to the other extragalactic FRBs. An untargeted ZTF r-band observation for FRB 20200120E (Andreoni et al. 2021) and the targeted (but nonsimultaneous) gri-band observations with ARCTIC on the Apache Point Observatory (APO) 3.5 m telescope (Huehnerhoff et al. 2016) for FRB 20180916B (Kilpatrick et al. 2021) probe a luminosity range of ~ 2 × 10^{38}–4 × 10^{40} erg s^-1 within ~ 10^3 s of radio bursts.

On a shorter timescale, several targeted high-speed simultaneous observations — by ULTRASPEC on the 2.4 m Thai National Telescope (TNT; Tulloch & Dhillon 2011; Dhillon et al. 2014) for FRB 20121102A (Hardy et al. 2017); the central pixel of the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes (Lacarelli et al. 2008; Hassan et al. 2021) for FRB 20121102B (MAGIC Collaboration et al. 2018); and Tomo-e Gozen on the Kiso 105 cm Schmidt telescope (Sako et al. 2018) for FRB 20190520B (Niino et al. 2022) — span a temporal range ~ 1–10 ms before/after radio bursts with a luminosity upper limit range of ~ 10^{45–47} erg s^-1 in a single exposure (longer and deeper stacked exposures are also shown in Figure 2). In the ZTF archival search, we also find a simultaneous 30 s r-band observation of FRB 20121102A with a luminosity limit of ~ 6 × 10^{43} erg s^-1.

Among the simultaneous optical observations, our KeplerCam and LCO r-band limits for FRB 20220912A are the deepest to date in terms of luminosity for the extragalactic FRBs, ~ (0.3–2.9) × 10^{42} erg s^-1 with 30–400 s exposures (i.e., excluding the Burst Observer and Optical Transient Exploring System, BOOTES, Z-band limit of ~ 1.8 × 10^{35} erg s^-1 with a 60 s exposure for the Galactic SGR 1935+2154; Lin et al. 2020). Our nearly simultaneous Binospec limit for FRB 20220912A is at ~ 2 × 10^{41} erg s^-1 with a 15 s exposure started at 0.4 s after a burst.

3.2. Optical-to-Radio Flux and Fluence Ratio Limits

To place the optical limits in the context of the individual FRB burst properties, we plot the ratio of optical flux limit to FRB radio fluence, f_{opt}/F_{radio}, in Figure 3. We make this parameter choice because the optical burst duration (t_{opt}) is not known. If the fluence measurement of a particular radio burst is not yet published, it is assumed to be the mean of the fluence distribution.
Limits on Optical Emission from Well-localized FRBs

Figure 2. Optical luminosity limits (in the $g$, $c$, $r$, $o$, $i$, and $z$ bands from the top to bottom rows) with respect to the temporally closest FRB detection for our sample of eight repeating FRBs (including the Galactic SGR 1935+2154). Representative limits are shown for the targeted high-speed observations (TNT $i$ and $i+z$, MAGIC $U$, Tomo-e open) in the panels with the closest filter effective wavelength, and similarly for LCO $R$ and BOOTES $Z$ and clear bands. A typical luminosity error in each band for SGR 1935+2154 (due to the large extinction and distance uncertainties) is shown as the magenta vertical bar. Our KeplerCam and LCO limits for FRB 20220912A (enclosed by the black rectangle) are the deepest among the simultaneous observations of extragalactic FRBs. Optical data sources: KeplerCam (this work for FRB 20220912A), LCO (this work and Lin et al. 2020 for FRBs 20200120E and 20220912A in $griz$, and SGR 1935+2154 in $R$, respectively), Binospec (this work for FRB 20220912A), ZTF (Andreoni et al. 2021, 2020 for FRBs 20200120E and 20180916B, respectively), ZTF forced-photometry service (Masci et al. 2019 and this work for all the FRBs), ATLAS forced photometry server (Shingles et al. 2021 and this work for all the FRBs), APO (Kilpatrick et al. 2021 for FRB 20180916B), TNT (Hardy et al. 2017 for FRB 20121102A), MAGIC (MAGIC Collaboration et al. 2018 for FRB 20121102A), Tomo-e (Niino et al. 2022 for FRB 20190520B), and BOOTES (Lin et al. 2020 for SGR 1935+2154). (The data used to create this figure are available.)
Figure 3. Ratio of optical flux limit (in janskys; in the $g$, $c$, $r$, $o$, $i$, and $z$ bands from the top to bottom rows) to radio fluence (in janskys times millisecond) with respect to the temporally closest FRB detection for our sample of eight repeating FRBs (including the Galactic SGR 1935+2154); labels are as in Figure 2. In the case when the radio fluence of a particular burst is not available, it is assumed to be the mean of the fluence distribution of that particular repeating FRB (and shown as a transparent point with an upper error bar corresponding to one standard deviation). The dashed and dotted gray lines in each panel show $F_{\text{opt}}/F_{\text{radio}} = 1$, 0.1, 0.01, and 0.001 assuming $F_{\text{opt}} = f_{\text{opt}} \times \Delta t$, where $\Delta t$ is the time delay between the optical and radio observations. Note that most of the simultaneous observations (KeplerCam, LCO, TNT, MAGIC, Tome-e, BOOTES), targeted Binospec and APO, and some untargeted ZTF observations are in the regime of $F_{\text{opt}}/F_{\text{radio}} \lesssim 1$. Our KeplerCam and LCO limits for FRB 20220912A are comparable even to the BOOTES simultaneous observation of SGR 1935+2154 ($f_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-7}$ ms$^{-1}$, or $F_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-3}$). Our nearly simultaneous Binospec limit is at $f_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-8}$ ms$^{-1}$, or $F_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-4}$ at $\Delta t \approx 0.4$ s.
of the relevant repeating FRB (e.g., the recently discovered FRB 20220912A). We find that the range of flux-to-fluence ratio limits is $\sim 10^{-9}$–0.1 ms$^{-1}$, on a timescale of $\gtrsim 10^3$ s.

If we make a conservative assumption that the optical counterpart duration is $t_{\text{opt}} \approx \Delta t$, where $\Delta t$ is the time delay between an FRB and an optical observation, we find that all of the targeted simultaneous observations lie below the critical line of $f_{\text{opt}}/F_{\text{radio}} \approx \frac{F_{\text{opt}}}{F_{\text{radio}}} = 1$. On the other hand, nearly all of the untargeted and archival observations are above the $F_{\text{opt}}/F_{\text{radio}} = 1$ line (Figure 3), meaning that they provide weak constraints for any model in which the energy release per frequency in the optical band is at most comparable to that in the radio bursts; exceptions are some nonsimultaneous APO and untargeted ZTF observations for FRBs 20180916 and 20220912A, respectively. Our nearly simultaneous Binospec limit is at $f_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-8}$ ms$^{-1}$ (or $F_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-4}$) at $\Delta t \approx 0.4$ s, which is the deepest for any FRBs on this timescale.

Among the simultaneous optical observations, our KeplerCam and LCO $r$-band limits for FRB 20220912A are the deepest to date in terms of $f_{\text{opt}}/F_{\text{radio}}$ for any extragalactic FRB, and indeed comparable to limits for the Galactic SGR 1935+2154, with $f_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-5}$ ms$^{-1}$. In terms of fluence ratios, our observations place a limit of $F_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-3}$. Our nearly simultaneous Binospec limit would be the deepest if it were indeed simultaneous given the aforementioned shutter timing uncertainty. We stress that these fluence ratio limits are lower than the observed values for the Crab and Geminga pulsars (e.g., Danilenko et al. 2011; Bühler & Blandford 2014), which may suggest a different emission mechanism (although pulsars with lower fluence ratios have also been observed; see, e.g., Niino et al. 2022 for a discussion for FRB 20190520B in this context).

3.3. Constraints on Fast Optical Burst Models

To constrain possible fast optical bursts on a comparable timescale to the radio bursts, we define an effective optical flux limit on a timescale, $t_{\text{opt}}$ (see also Lyutikov & Lorimer 2016):

$$f_{\text{eff, opt}} = f_{\text{opt}} \frac{T_{\text{exp}}}{t_{\text{opt}}},$$

where $T_{\text{exp}}$ is the exposure time. For the sample of FRBs with simultaneous optical observations, we show $f_{\text{eff, opt}}/F_{\text{radio}}$ as a function of $t_{\text{opt}}$ in Figure 4. The previously published high-speed observations of FRBs 20121102A and 20190520B only probe $f_{\text{eff, opt}}/F_{\text{radio}} \gtrsim 0.1$ on millisecond timescales, and reach $f_{\text{eff, opt}}/F_{\text{radio}} \sim 0.01$ only on $\gtrsim$ second timescales due to the shallow integrated flux limit (i.e., apparent magnitude limit).

On the other hand, our KeplerCam and LCO observations for FRB 20220912A are far more sensitive, reaching $f_{\text{eff, opt}}/F_{\text{radio}} \lesssim 0.02$ on a millisecond timescale, and $\lesssim 3 \times 10^{-5}$ on a second timescale. These limits are only an order of magnitude higher than the limits for the Galactic SGR 1935+2154. Our nearly simultaneous Binospec observation for FRB 20220912A reaches $f_{\text{eff, opt}}/F_{\text{radio}} \lesssim 10^{-6}$ on a second timescale (and $\lesssim 10^{-3}$ on a millisecond timescale if it were indeed simultaneous, which is on the same order as the SGR 1935+2154 limits.

We also plot in Figure 4 broad ranges of some optical burst models from Yang et al. (2019). In these models the subsequent optical bursts to FRBs originate from several inverse-Compton scattering processes involving a highly magnetized central source, such as a young pulsar or magnetar. One-zone models (e.g., pulsar magnetosphere and maser outflow) are expected to have $t_{\text{opt}} \approx t_{\text{FRB}}$, while two-zone models could result in a much longer timescale for the optical emission given the larger scattering region than FRB emission region (e.g., $\sim 5000$ s for the pulsar nebula model; Yang et al. 2019). The optical constraints for FRBs 20121102A and 20190520B from previous observations barely reach the upper end of the pulsar nebula model with $t_{\text{opt}} \sim 0.1$–10 s. Those of SGR 1935+2154 are well within the model predictions for pulsar magnetosphere and nebula (see also Lin et al. 2020). For the first time for an extragalactic FRB, our limits for FRB 20220912A also reach the model prediction ranges. Within these models, these limits provide meaningful constraints on the magnetic field of $B \lesssim 10^{14}$ G for magnetars or the spin period of $P \lesssim 0.01$ s for young pulsars.

In Figure 4, we also show potential constraints from high-speed observations with a large-aperture telescope, specifically the Subaru High-Speed Suprime-Cam (HSSC), a planned upgrade for the Suprime-Cam instrument. These potential future observations can provide limits of $f_{\text{eff, opt}}/F_{\text{radio}} \lesssim 0.01$–10$^{-4}$ on millisecond to second timescales for FRBs 20121102A and 20190520B, reaching the pulsar magnetosphere and pulsar nebula model parameter space. For FRB 20220912A and SGR 1935+2154, these observations would probe...
3.4. Constraints on the Synchrotron Maser Model

To place the luminosity limits on a longer timescale into context, we compare them with theoretical light curves from the synchrotron maser model (Metzger et al. 2019; Margalit et al. 2020a,b). In this model, relativistic plasma ejected from a central engine (e.g., a magnetar) creates a shock in the external magnetized medium (produced in previous flare events), resulting in an FRB from synchrotron maser emission (Plotnikov & Sironi 2019). The model predicts that a broadband synchrotron afterglow will follow the FRB and peak in gamma- to X-rays on a millisecond timescale and in optical on minute to
hour timescales. We provide details of the model (including the relevant equations) in Appendix B and show model light curves in Figure B1. Assuming an external medium with a constant (shell-like) density distribution, the afterglow light curves are parameterized by the flare energy ($E_{\text{flare}}$) ejecting the relativistic plasma and the external density ($n_{\text{ext}}$) at the shock front; we note that the density structure could in reality be more complex, either wind-like ($\propto r^{-2}$) or a combination of multiple structures (e.g., see Cooper et al. 2022 for the case of SGR 1935+2154).

We explore $E_{\text{flare}}$ and $n_{\text{ext}}$ ranges of $10^{37}$–$10^{39}$ erg and $10$–$10^7$ cm$^{-3}$, respectively, for each FRB, except the Galactic SGR 1935+2154, where we use a lower $E_{\text{flare}}$ bound of $10^{32}$ erg. We calculate a model light curve (in terms of specific luminosity at each optical filter effective wavelength) for every combination of $E_{\text{flare}}$ and $n_{\text{ext}}$ and compare each optical limit with the integrated average over the exposure time. If the model light curve is brighter than the optical limit, we consider the specific combination of $E_{\text{flare}}$ and $n_{\text{ext}}$ parameter space as constrained. The results are shown in Figure 5, along with FRB-based estimates of $E_{\text{flare}}$ and $n_{\text{ext}}$ for each burst (see Equations (B6)–(B8)). The model light curves, and thus the optical constraints, are more sensitive to $E_{\text{flare}}$ than to $n_{\text{ext}}$ since the characteristic synchrotron frequency, above which the light curves decline exponentially, is set by $E_{\text{flare}}$ (see Equations (B1)–(B5)).

As shown in Figure 5, the existing optical constraints already reach the high-$E_{\text{flare}}$ ends of the distributions for FRB 20180916B ($\gtrsim 10^{44}$ erg; see also Kilpatrick et al. 2021) and SGR 1935+2154 ($\gtrsim 10^{39}$ erg; see also Cooper et al. 2022). The combination of our simultaneous KeplerCam and LCO observations, and nearly simultaneous deep Binospec observation (with only a 0.4 s delay), are the main drivers for constraining the FRB 20220912A parameter space ($\gtrsim 10^{45}$ erg) covering $\approx 65\%$ of its radio bursts observed to date (the ones with published flux/fluence information).

In Figure 5, we also show the potential constraints from future observations. Follow-up 60-300 s observations with 1–5 minutes delay using a 1 m class telescope (e.g., KeplerCam and LCO; limiting magnitude of 20–22) have the potential to reach the high-$E_{\text{flare}}$ end of the distribution of FRB 20201124A ($\sim 10^{46}$ erg). Similarly, simultaneous 0.1–1 sec observations using an 8 m class telescope (e.g., Subaru HSC) could potentially constrain the high-$E_{\text{flare}}$ end and mid-$E_{\text{flare}}$ range of the distributions of FRB 20200120E ($\sim 10^{39}$ erg) and SGR 1935+2154 ($\sim 10^{36}$ erg), respectively, if we could target them in an active phase.

4. SUMMARY AND CONCLUSIONS

We presented the most constraining limits on transient optical counterparts of FRBs to date, from dedicated simultaneous observations of 13 bursts from the repeating FRB 20220912A, and a nearly simultaneous observation with a 6.5 m MMT/Binospec delayed by only 0.4 s (which may indeed be simultaneous given the shutter timing uncertainty). We further presented our dedicated follow-up observations, and compiled all available serendipitous archival and published observations following bursts from a sample of eight repeating FRBs (including the Galactic SGR 1935+2154) and seven non-repeating FRBs. This data set, and in particular our simultaneous observations of FRB 20220912A, provides the largest study to date of optical emission associated with FRBs. None of the FRBs studied here presented detectable transient optical counterparts. Our key findings are as follows:

1. Nearly all archival optical observations have a delay of $\gtrsim 10^4$ s relative to the time of bursts, while targeted observations have shorter and even up to no delays providing some constraining limits.

2. Previous simultaneous observations provided optical luminosity limits of $\lesssim 10^{45}$ erg s$^{-1}$ (with the exception of SGR 1935+2154 with $\lesssim 10^{35}$ erg s$^{-1}$), while our simultaneous KeplerCam and LCO observations provide limits of $\lesssim 10^{42}$ erg s$^{-1}$, a three orders of magnitude improvement. Our nearly simultaneous Binospec observation reaches a limit of $\lesssim 2 \times 10^{41}$ erg s$^{-1}$.

3. Normalizing the optical fluence limits (using the time delay as a proxy for $t_{\text{opt}}$) by the radio fluences, most archival observations have $F_{\text{opt}}/F_{\text{radio}} \gtrsim 1$, and therefore place only weak constraints on the relative energy per frequency in the optical and radio. On the other hand, our simultaneous KeplerCam and LCO observations and nearly simultaneous deep Binospec observations place more meaningful limits of $F_{\text{opt}}/F_{\text{radio}} \lesssim 10^{-3}$ and $\lesssim 10^{-4}$, respectively (even comparable to/deeper than the limits obtained for SGR 1935+2154).

4. Comparing the simultaneous limits (normalized by radio flux), we find that previous observations did not constrain models for simultaneous optical bursts (with the exception of one observation of SGR 1935+2154), while our KeplerCam and LCO and nearly simultaneous Binospec observations of FRB 20220912A place the first meaningful constraints on model predictions, ruling out portions of the parameter space for some models.
Figure 5. FRB-based estimates (points) and optical-based constraints (shaded regions) on the external density ($n_{\text{ext}}$) and flare energy ($E_{\text{flare}}$) in the synchrotron maser model (Figure B1). The contours mark the number of most stringent optical limits (i.e., deeper limits with shorter delays; from left to right in each panel: 1, 5, 25, 50, 100, and 200) used to constrain the parameter space, while the gray dashed and dotted lines show the possible constraints from future observations: 60–300 s exposures (limiting magnitude of 20–22) with 1–5 minutes delay using a 1 m class telescope (e.g., KeplerCam and LCO), and simultaneous 0.1–1 s exposure (limiting magnitude of 20–22) using an 8 m class telescope (e.g., Subaru HSSC). Note that optical limits already reach the high-$E_{\text{flare}}$ ends of the distributions for FRB 20180916B and SGR 1935+2154, and down to the mid-$E_{\text{flare}}$ range ($\approx 65\%$) of the distribution of FRB 20220912A with our KeplerCam, LCO, and Binospec observations. The future observations have potential to reach FRBs 20200120E and 20201124A, and to constrain SGR 1935+2154 even further.
5. Interpreting the optical luminosity limits in the context of the synchrotron maser model, and comparing to the distributions of $E_{\text{flare}}$ and $n_{\text{ext}}$ inferred from the radio bursts for each repeating FRB, we find that most optical limits are not constraining (except the one limit for SGR 1935+2154), but our simultaneous and targeted observations of FRB 20220912A rule out the bulk of the parameter space for this model.

Given the estimated high burst rate of FRB 20220912A ($\sim$ a few hundreds per hour; Kirsten et al. 2022b; Bhusare et al. 2022; Feng et al. 2022a; McKinven & CHIME/FRB Collaboration 2022; Zhang et al. 2022a), and the fact that most searches have not published arrival times for their detected bursts, it is possible that we have simultaneous coverage for additional bursts (including multiple bursts in a single exposure added coherently, as in the KeplerCam and LCO exposures), which would place tighter constraints on the fast optical burst and synchrotron maser models. This will be explored once all the FRB measurements (e.g., arrival times, duration, flux, and fluence) become public. Indeed, to enable this type of work on a rapid timescale, we advocate for FRB search efforts to make these basic properties public in real time.

We further investigate the potential of future follow-up and coordinated simultaneous observations using $1$–$8$ m class telescopes on a wide range of timescales from milliseconds to minutes. We find that these observations have the potential to better constrain optical emission from FRBs compared to the bulk of serendipitous archival observations. In particular, based on the experience and constraining limits from our KeplerCam, LCO, and Binospec observations, as well as previous targeted observations (e.g., Hardy et al. 2017; MAGIC Collaboration et al. 2018; Kilpatrick et al. 2021; Niino et al. 2022), we advocate for an approach of simultaneous monitoring of FRBs during CHIME (or other facility) observing windows, especially when repeating FRBs are in a particularly active phase.

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### Table A1. Well-localized Non-repeating FRB Sample

| FRB    | R.A. (deg) | Decl. (deg) | Redshift (z) | $d_L$ (Mpc) | $A_{V, MW}$ (mag) | Frequency (GHz) | DM (pc cm$^{-3}$) | Width (ms) | Flux (Jy) | Fluence (Jy ms) |
|--------|------------|-------------|--------------|-------------|-------------------|----------------|-----------------|------------|----------|---------------|
| 20190608B | 334.01988(1) | -7.89825(8) | 0.1178 | 541 | 0.125 | 1.295 | 338.7(5) | 6.0(8) | ∼ 4.3 | 26(4) |
| 20200430A | 229.70642(8) | +12.3769(3) | 0.160 | 755 | 0.112 | 0.8645 | 380.1(4) | - | - | 35(4) |
| 20190714A | 183.9797(1) | -13.02103(8) | 0.2365 | 1167 | 0.166 | 1.2725 | 504(2) | - | - | 8(2) |
| 20191228A | 344.4304(3) | -29.5941(3) | 0.2432 | 1204 | 0.065 | 1.2715 | 297.5(5) | 2.3(6) | ∼ 17 | 40$^{+10}_{-4}$ |
| 20200906A | 53.4962(1) | +73.70675(8) | 0.6 | 3480 | 0.371 | 1.4 | 959(5) | ∼ 5.0 | 0.12(1) | 0.62(7) |
| 20200906A | 65.07554(8) | +73.70675(8) | 0.6 | 3480 | 0.371 | 1.4 | 959(5) | ∼ 5.0 | 0.12(1) | 0.62(7) |

Note—Measurements of each individual burst are published in its entirety in machine-readable form.

$a$ Calculated from the host redshift assuming a standard $\Lambda$CDM cosmology with $H_0 = 71.0$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$.

$b$ From Schlafly & Finkbeiner (2011), retrieved via IRSA.

$c$ If only two of the width ($t_{FRB}$), flux ($F_{radio}$), and fluence ($F_{radio}$) are reported for a particular burst, the third parameter is estimated assuming $F_{radio} \sim f_{radio} t_{FRB}$.

$d$ Localized with ASKAP and the host spectroscopic redshift measured from an archival SDSS spectrum (Day et al. 2020; Macquart et al. 2020).

$e$ Localized with ASKAP and the host spectroscopic redshift measured with Nordic Optical Telescope (NOT; Heintz et al. 2020; Kumar et al. 2020).

$f$ Localized with ASKAP and the host spectroscopic redshift measured with Keck (Bhandari et al. 2019; Heintz et al. 2020).

$g$ Localized with ASKAP and the host spectroscopic redshift measured with Keck (Shannon et al. 2019; Bhandari et al. 2022).

$h$ Localized with ASKAP and the host spectroscopic redshift measured with Keck (Bhandari et al. 2022).

$i$ Localized with VLA and the host photometric redshift estimated from spectral energy distribution fits (Law et al. 2020).

$j$ Localized with DSA and the host spectroscopic redshift measured with Keck (Ravi et al. 2019).

### APPENDIX

#### A. OPTICAL CONSTRAINTS FOR WELL-LOCALIZED NON-REPEATING FRBS

We summarize the well-localized non-repeating FRB sample and their references in Table A1. The same luminosity and flux analyses as for the repeating FRBs are performed and shown in Figures A1 and A2, except for the simultaneous flux analysis since no such measurements are available given the unpredictable nature of one-off FRBs. We find that none of the optical limits are particularly constraining. Nevertheless, we also compare the luminosity limits to the light curves from the synchrotron maser model (although its application is somewhat questionable given the one-off nature of these events), concluding that only the very high-$E_{flare}$ end ($\gtrsim 10^{48}$ erg) could be constrained. These constraints are at least three orders of magnitude larger than the FRB-based estimates (where available).
Table A1 summarizes the non-repeating FRBs. The luminosity and temporal ranges are much less constraining compared to the repeating FRBs due to the small number of bursts and their large distances. Optical data sources include LCO (Núñez et al. 2021 for FRBs 20190608B and 20190714A in the $r$ band), ZTF forced-photometry service (Masci et al. 2019 and this work for all the FRBs), and ATLAS forced photometry server (Shingles et al. 2021 and this work for all the FRBs). (The data used to create this figure are available.)
Figure A2. Same as Figure 3, but for the non-repeating FRBs. Note that all available observations are in $F_{\text{opt}}/F_{\text{radio}} \gtrsim 1$ regime.
B. SYNCHROTRON MASER MODEL

With some modifications, we follow Kilpatrick et al. (2021) for the application of the synchrotron maser model of Metzger et al. (2019), Margalit et al. (2020a), and Margalit et al. (2020b) to their optical limits on the well-localized repeating FRB 20180916B. In this model, the prompt radio emission (i.e., FRB) and afterglow gamma-ray to optical emission originate from the shock interaction between magnetar/pulsar-ejected plasma and the highly magnetized external medium. The characteristic synchrotron frequency ($\nu_{\text{syn}}$) is set by the flare energy ($E_{\text{flare}}$):

$$h\nu_{\text{syn}}(t_{\text{FRB}}) = 57\text{ MeV} \left( \frac{\sigma}{0.1} \right)^{1/2} \left( \frac{E_{\text{flare}}}{10^{43}\text{ erg}} \right)^{1/2} \left( \frac{t_{\text{FRB}}}{\text{ms}} \right)^{-3/2}$$

(B1)

where $t_{\text{FRB}}$ is the FRB duration (or width) and $\sigma$ is the fractional magnetization (see Equations (56) and (57) of Metzger et al. 2019). In this work, we adopt a fiducial $\sigma = 0.3$ (Plotnikov & Sironi 2019). The time evolution of the synchrotron frequency is as follows:

$$\nu_{\text{syn}}(t) = \begin{cases} \nu_{\text{syn}}(t_{\text{FRB}}) \left( \frac{t}{t_{\text{FRB}}} \right)^{-1} & \text{for } t < t_{\text{FRB}} \\ \nu_{\text{syn}}(t_{\text{FRB}}) \left( \frac{t}{t_{\text{FRB}}} \right)^{-3/2} & \text{for } t > t_{\text{FRB}} \end{cases}$$

(B2)

Assuming a constant (shell-like) external density ($n_{\text{ext}}$) at the shock front, the cooling frequency ($\nu_{\text{cool}}$) can be expressed as a function of time (see Equations (32) and (60) of Metzger et al. 2019 and also Equation (4) of Kilpatrick et al. 2021):

$$h\nu_{\text{cool}}(t) = 2.3\text{ keV} \left( \frac{\sigma}{0.1} \right)^{-3/2} \left( \frac{n_{\text{ext}}}{10^3\text{ cm}^{-3}} \right)^{-1} \left( \frac{t}{10^{-3}\text{ s}} \right)^{-1/2}$$

(B3)

Then, the peak luminosity ($L_{\text{peak}}$) and specific luminosity ($L_\nu$) can be written as a function of frequency (see Equations (63) and (64) of Metzger et al. 2019):

$$L_{\text{peak}}(t) = 10^{45}\text{ erg s}^{-1} \left( \frac{E_{\text{flare}}}{10^{43}\text{ erg}} \right) \left( \frac{t}{10^{-3}\text{ s}} \right)^{-1},$$

(B4)

$$\nu L_\nu(t) = \begin{cases} \left( L_{\text{peak}} \nu_{\text{cool}} \right)^{4/3} \left( \frac{\nu_{\text{cool}}}{\nu_{\text{syn}}} \right)^{1/2} \propto t^{1/6} & \text{for } \nu < \nu_{\text{cool}} \\ \left( L_{\text{peak}} \nu_{\text{syn}} \right)^{1/2} \propto t^{-1/4} & \text{for } \nu_{\text{cool}} < \nu < \nu_{\text{syn}} \\ L_{\text{peak}} e^{-\nu/\nu_{\text{syn}} - 1} \propto t^{-1} e^{-\nu^{3/2}} & \text{for } \nu_{\text{syn}} < \nu \end{cases}$$

(B5)

where we adopt an exponential cutoff above $\nu_{\text{syn}}$, as in Kilpatrick et al. (2021). The time dependence is shown for $t > t_{\text{FRB}}$. Representative model light curves in the $r$ band ($\nu = 5 \times 10^{14}\text{ Hz}$) for various choices of $E_{\text{flare}}$ and $n_{\text{ext}}$ are shown in Figure B1.

From FRB measurements of the radio fluence ($F_{\text{radio}}$) and frequency ($\nu_{\text{obs}}$), the isotropic radio energy ($E_{\text{radio}}$) and flare energy can be estimated as

$$E_{\text{radio}} = 9.5 \times 10^{31}\text{ erg} \left( \frac{4\pi}{1+z} \right) \left( \frac{dL}{\text{Mpc}} \right)^2 \left( \frac{F_{\text{radio}} \nu_{\text{obs}}}{\text{Jy ms GHz}} \right),$$

(B6)

$$\frac{E_{\text{flare}}}{E_{\text{radio}}} = 3.3 \times 10^4 \left( \frac{f_e}{0.5} \right)^{-1/5} \left( \frac{f_\xi}{10^{-3}} \right)^{-4/5} \left( \frac{\nu_{\text{obs}} t_{\text{FRB}}}{\text{GHz ms}} \right)^{1/5},$$

(B7)

where $f_e$ and $f_\xi$ are the number density ratio of electrons to ions in the upstream medium and the synchrotron maser efficiency, respectively (see Equation (14) of Margalit et al. 2020a). In this work, we assume fiducial $f_e = 0.5$ and $f_\xi = 10^{-3}$ (Plotnikov & Sironi 2019). The external density can also be estimated from FRB measurements as

$$n_{\text{ext}} = 420\text{ cm}^{-3} \left( \frac{m_\star}{m_e} \right)^{2/15} \left( \frac{f_e}{0.5} \right)^{-11/15} \left( \frac{f_\xi}{10^{-3}} \right)^{-4/15} \times \left( \frac{\nu_{\text{obs}}}{\text{GHz}} \right)^{31/30} \left( \frac{t_{\text{FRB}}}{\text{ms}} \right)^{2/5} \left( \frac{E_{\text{radio}}}{10^{40}\text{ erg}} \right)^{-1/3},$$

(B8)

where $m_\star$ and $m_e$ are the masses of upstream particles and electrons (see Equation (8) of Margalit et al. 2020b). In this work, we assume a pair plasma (i.e., $m_\star = m_e$). Then, these FRB-based estimates for $E_{\text{flare}}$ and $n_{\text{ext}}$ can be compared with the optical constraints, as in Figure 5.
Figure B1. Frequency and luminosity evolution (in the $r$ band) of the synchrotron maser model (Metzger et al. 2019; Margalit et al. 2020a,b) with an FRB duration $t_{\text{FRB}} = 1$ ms, assuming a shell-like density distribution and fractional magnetization $\sigma = 0.3$ (see Equations (B1)–(B5)). The light curves exhibit changing evolution in each frequency regime ($\nu_r < \nu_{\text{cool}}$, $\nu_{\text{cool}} < \nu_r < \nu_{\text{syn}}$, and $\nu_{\text{syn}} < \nu_r$). Left: models with a fixed density of $n_{\text{ext}} = 2000$ cm$^{-3}$, color-coded by $E_{\text{flare}}$. Right: models with a fixed flare energy of $E_{\text{flare}} = 10^{46}$ erg, color-coded by $n_{\text{ext}}$. 