Deep Optical Observations Contemporaneous with Emission from the Periodic FRB 180916+J0158+65

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Received 2020 November 15; revised 2020 December 18; accepted 2020 December 18; published 2021 January 14

Abstract

We present deep Apache Point Observatory optical observations within seconds of radio emission from the periodic fast radio burst (FRB) 180916+J0158+65 obtained on 2020 September 3. FRB 180916+J0158+65 is located in a nearby spiral galaxy 150 Mpc away and has an “active phase” with a well-measured period of approximately 16.3 days. Targeting the FRB at the peak of its expected active phase and during a recent 30 minute observing window by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) in which a radio burst was detected, we did not detect any transient optical emission at $m_i \approx 24.7$ mag ($3\sigma$) from 2.2 to 1938.1 s after the burst arrival time in optical bands (corrected for dispersion). Comparing our limiting magnitudes to models of a synchrotron maser formed in the circumburst environment of FRB 180916+J0158+65, we constrain scenarios where the burst energy was $>10^{44}$ erg and the circumburst density was $>10^6$ cm$^{-3}$.

Unified Astronomy Thesaurus concepts: Radio transient sources (2008); Transient sources (1851); Radio bursts (1339)

1. Introduction

Fast radio bursts (FRBs) are millisecond-timescale (Lorimer et al. 2007) bursts of MHz–GHz radio emission from extragalactic sources (Thornton et al. 2013; CHIME/FRB Collaboration et al. 2019; Cordes & Chatterjee 2019; Petroff et al. 2019, and references therein). The detection of the first repeating FRB 121102 (Spitler et al. 2014, 2016) enabled its precise localization in a host galaxy at $z = 0.193$ (Chatterjee et al. 2017). There may also be a non-repeating population of FRBs (e.g., Ai et al. 2021; Hashimoto et al. 2020), but the observed FRB rate and luminosity function suggests that most of these sources must be repeating (whether or not they are observed to repeat, e.g., Caleb et al. 2019; Ravi et al. 2019). In addition, a handful of FRBs have been accurately localized and securely associated with host galaxies, spanning a wide range of host types from star-forming to quiescent galaxies (e.g., FRB 121102, 180916, 180924, 190711; Chatterjee et al. 2017; Bhandari et al. 2018; Bannister et al. 2019; Heintz et al. 2020; Kumar et al. 2021; Li & Zhang 2020; Macquart et al. 2020; Marcote et al. 2020).

Several hypotheses have been proposed for FRB progenitor systems (Platts et al. 2019), from eruptions on the surfaces of highly magnetized neutron stars (i.e., magnetars; Popov & Postnov 2013; Kulkarni et al. 2014; Lyubarsky 2014; Katz 2016; Beloborodov 2017; Kumar et al. 2017; Metzger et al. 2017; Wadiasingh & Timokhin 2019; Beniamini et al. 2020) to accretion-induced collapse of neutron stars into black holes (Falcke & Rezzolla 2014). Notably, the recent detection of an FRB-like event from the Galactic magnetar SGR 1935 +2154 suggests that at least a subset of repeating, extragalactic FRBs originate from magnetars (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020a; Lu et al. 2020; Margalit et al. 2020a). This interpretation is complicated in part by evidence that FRB hosts lack a clear association to star formation (although some studies suggest FRBs can be produced via magnetars that do not trace star formation; see, e.g., Margalit et al. 2019; Bochenek et al. 2020; Safarzadeh et al. 2020).

Precise localization of FRBs has also enabled both targeted and untargeted follow up at wavelengths spanning from optical (Hardy et al. 2017; Bhandari et al. 2018; Andreoni et al. 2020) to X-ray (Petroff et al. 2015; Scholz et al. 2016; Pilia et al. 2020; Tavani et al. 2020; Scholz et al. 2020) to gamma-ray wavelengths (Yamasaki et al. 2016; Best & Bazo 2019; Cunningham et al. 2019, 2020, 2020) primarily for the well-localized, repeating bursts FRB 121102 and FRB 180916. So far these searches have revealed no potential counterparts for extragalactic FRBs (e.g., Chen et al. 2020) apart from a 100 s duration gamma-ray transient detected at the 3.2$\sigma$ level by the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004) and contemporaneous with a burst from FRB 131104 (DeLaunay et al. 2016), although the association may not be secure (Gao & Zhang 2017; Shannon & Ravi 2017).

Theoretical models for optical FRB emission span a wide range of luminosities and timescales from $>10^{41}$ erg s$^{-1}$ on the timescale of the burst (Lyuubysky 2014; Beloborodov 2017) to fainter ($<10^{40}$ erg s$^{-1}$) afterglows that may last for seconds to minutes (Metzger et al. 2019). However, the best limits from optical follow-up observations have only ruled out counterparts to bursts down to relatively unconstraining luminosities of $\approx10^{45}$ erg s$^{-1}$ (Hardy et al. 2017) within milliseconds of a burst or $\approx5 \times 10^{45}$ erg s$^{-1}$ within minutes of a burst.
(Andreoni et al. 2020). Recent constraints on the periodic activity window of the repeating FRB 180916.J0158+65 (hereafter FRB 180916; CHIME/FRB Collaboration et al. 2020b) offer a unique opportunity to target emission from a FRB counterpart at non-radio wavelengths. In addition to untargeted optical observations from the Zwicky Transient Facility (Andreoni et al. 2020), Pilia et al. (2020) and Zampieri et al. (2020) reported high-speed optical observations with the 1.2 m Galileo telescope, although no burst occurred during these observations. Additional multi-band follow up of this source will further benefit from the known 16.3 day period, suggesting that the counterpart is highly active on this timescale (CHIME/FRB Collaboration et al. 2020b). The relatively low redshift \( z = 0.0337 \) with an implied luminosity distance of \( D_L \approx 150 \text{ Mpc} \); Marcote et al. 2020; CHIME/FRB Collaboration et al. 2020b) means that any observations will yield significantly deeper constraints than those for FRBs previously targeted at optical wavelengths (e.g., FRB 121102 at \( z = 0.1927 \); Hardy et al. 2017; Tendulkar et al. 2017; Bhandari et al. 2018).

Here we discuss targeted optical follow-up of FRB 180916 with the Apache Point Observatory (APO) 3.5 m telescope. These observations were obtained contemporaneously with observations from the Canadian Hydrogen Intensity Mapping Experiment (CHIME) on 2020 September 3. During the observations, CHIME detected a radio burst at a location and dispersion measure consistent with previous bursts from FRB 180916 (CHIME/FRB Collaboration et al. 2020b; Marcote et al. 2020). At the time of the burst and for 30 minutes thereafter, we observed the FRB 180916 host galaxy with the APO telescope, but we did not detect any transient optical emission at the FRB site. Based on the non-detections, we place constraints on the allowed burst properties and circumburst density in the synchrotron maser model. We discuss the timing and details of our observations in Section 2. In Section 3, we analyze these limits in the context of realistic optical counterparts to FRBs and discuss the implications of these limits for future follow-up efforts. We summarize our findings in Section 4.

2. Observations

We targeted FRB 180916 on 2020 September 3 with the APO 3.5 m telescope, mounted with the Astrophysical Research Consortium Telescope Imaging Camera (ARCTIC; Huehnerhoff et al. 2016). Our observations began (i.e., the camera shutter opened) at UTC 2020-09-03 11:05:39.7503. Each exposure sequence was a \( 3 \times 30.33 \) s set of images in a single band (except for the third and fourth set of g-band exposures, which consisted of two and four exposures, respectively), following a \( ai \rightarrow r \rightarrow g \) pattern for nine images per pattern or 36 images over the full set of observations (Table 1). The average time per exposure is 30.3 s over 2221.7 s for an observing efficiency of \( \approx 49\% \). In addition, we obtained follow-up observations on 2020 September 13 in gri bands with \( 3 \times 100 \) s exposures to use as templates for comparison to the previous epoch. We show example r- and i-band images obtained within 2 min from the topocentric radio burst arrival time in Figure 1.

The radio burst occurred during our first gri sequence when the second r-band image was exposing, implying that 32 out of 36 of our exposures occurred around or after the burst arrival time. Based on the topocentric burst time at 400 MHz provided by CHIME, the radio burst arrival time was 6.908 s after the shutter opened and 23.442 s before the shutter closed for this exposure. Thus, including the second r-band exposure, approximately \( 32 \times 30.33 \) s of cumulative exposure time was obtained during or immediately after the time of burst. The exact time the shutter opened and closed is given in Table 1 along with the relative time (in seconds) from the radio burst arrival.

The dispersion measure (DM) for the FRB 180916 burst on 2020 September 3 was \( 352.6 \pm 3.2 \) pc cm\(^{-3} \), consistent with previous measurements toward the repeater (CHIME/FRB Collaboration et al. 2020b; Marcote et al. 2020). Based on this measurement, we estimate the arrival time for the corresponding r-band optical emission from the FRB observed at 400 MHz, which would be earlier as it occurred at a higher frequency. Following Equation (1) in Cordes & Chatterjee (2019; see also Tananbaum et al. 1968), we estimate that the burst arrival time in the optical was 9.1 s earlier than at 400 MHz, implying an arrival time of UTC 2020-09-03 11:10:23.4. There is also some delay associated with the difference in light travel time between CHIME and APO, but as these locations are \( \approx 2000 \) km apart, the delay would only be of order 7 ms, which is negligible compared to the uncertainty on the optical arrival time. Therefore, we use UTC 2020-09-03 11:10:23.4 throughout this Letter as the reference point for the “dispersion-corrected burst arrival time.”

We reduced all ARCTIC data using a custom-built pipeline based on the photpipe imaging and photometry package (Rest et al. 2005; Kilpatrick et al. 2018). Each frame was corrected for bias and flat-fielded using bias and sky flat-field frames obtained in the same instrumental configuration. We registered the images using 2MASS astrometric standards (Skrutskie et al. 2006) observed in the field of each image. Finally, we performed point-spread function (PSF) photometry using DoPhot (Schechter et al. 1993) and calibrated the gri data using Pan-STARRS Data Release 2 (PS1 DR2) standard stars in each image (Flewelling et al. 2020). We subtracted the observations taken on 2020 September 13 from all 2020 September 3 observations using HOTPANTS (Becker 2015) to perform PSF convolution and difference imaging and then estimated the \( 3\sigma \) limiting magnitude at the position of FRB 180916 (from Marcote et al. 2020) with fake star injection. Thus, the limits that we derive can be interpreted as the maximum average in-band specific flux integrated over the 30.33 s window for each exposure or the entire observation window for the limits in the stacked data. As shown in Table 1, the typical limiting magnitude of each individual frame was \( \approx 24.5 \) mag in gri bands or \( \approx 26.0 \) mag in the stacked frames.

3. Constraining the FRB Emission Mechanism

The timeline for our exposures immediately after the radio burst is shown in Figure 2. We estimate based on the 9.1 s dispersive delay of the radio emission that the FRB occurred approximately 2.2 s before the shutter opened for our second r-band exposure. Thus our closest and most constraining image of FRB 180916 covered roughly 2.2 to 30.5 s relative to the burst arrival time. Our full, post-burst data set covers approximately +2.2 s to +19.38 s relative to the dispersion-corrected burst arrival time in gri (Table 1). There are also four
exposures before the predicted dispersion-corrected burst arrival time, but in the context of the models below, we do not consider these data as no optical emission is predicted.

We give the $3\sigma$ limiting magnitude in AB magnitudes both for a source at the location of FRB 180916 in each image and in absolute magnitudes after correcting for the distance modulus and Milky Way foreground extinction $A_V = 2.767$ mag (from Schlafly & Finkbeiner 2011). We assume the redshift $z = 0.0337 \pm 0.0002$ derived for the host galaxy of FRB 180916 in Marcote et al. (2020) along with Planck Collaboration et al. (2016) cosmology, from which we derive a luminosity distance of $D_L = 153 \pm 1$ Mpc or a distance modulus of $\mu = 35.92 \pm 0.02$ mag.

We compare these limits to predictions of the synchrotron maser model as shown in Metzger et al. (2019); Margalit et al. (2020); but also see Lyubarsky 2014; Beloborodov 2017, 2020, for slightly different optical predictions, especially at times comparable to the burst duration when the total luminosity may be larger). This specific model was chosen because it predicts relatively long-lived optical emission on timescales comparable to those of our observations depending on the parameters chosen. This is in contrast to optical emission predicted in

Notes.

$^a$ All times are UTC on 2020-09-03. The relative epoch is given in seconds compared with the dispersion-corrected burst arrival time (UTC 2020-09-03 11:10:23.4) as described in Section 2.

$^b$ Pointing center of our ARCTIC observation. Note that ARCTIC is a 2048 $\times$ 2048 imager with $\approx0.6$ pixels, for a $7.92 \times 7.92$ field of view.

$^c$ $3\sigma$ apparent limiting magnitude at the location of FRB 180916 averaged over the entire exposure.

$^d$ $3\sigma$ absolute limiting magnitude accounting for a distance modulus $\mu = 35.92$ mag (Section 3) and foreground extinction from Schlafly & Finkbeiner (2011). The values in this table assume no interstellar host extinction, but we adopt $A_V = 0.53$ mag, $A_R = 0.37$ mag, and $A_G = 0.27$ mag following the discussion in Section 3.

$^e$ Stacked exposure for all imaging after the expected optical arrival time of the 2020 September 3 burst for FRB 180916. The limiting magnitude is $3\sigma$ calculated empirically in the stacked frame as described in Section 3.
models of Lyubarsky (2014), Beloborodov (2017), which predict more luminous optical emission on timescales comparable to the radio emission.

In the Metzger et al. (2019) formalism for this model, the radio burst originates in a shock from a radially expanding plasmoid launched from a central engine (e.g., a magnetar). The relativistic plasmoid may be decelerated by surrounding material in the immediate environment of the engine. If this material is sufficiently magnetized, synchrotron maser emission will be produced (Plotnikov & Sironi 2019). In the model of Metzger et al. (2019) and Margalit et al. (2020b; and first proposed by Beloborodov 2017) the surrounding upstream material is baryon-loaded ejecta expelled in previous flaring activity of the magnetar.

One prediction of this model (see Section 4 in Metzger et al. 2019) is that there should be a broadband (incoherent) synchrotron afterglow that will accompany and follow the FRB. On timescales similar to the FRB duration, this afterglow will peak in hard X-rays/gamma-rays, but it can subsequently cascade through optical bands on timescales of minutes post-burst. Assuming a plasmoid ejection event with energy $E_{\text{flare}}$ that lasts for a duration $t_{\text{FRB}}$, and a fractional magnetization $\sigma$ in the material upstream from the forward shock, the peak frequency $\nu_{\text{syn}}$ of this synchrotron afterglow will vary with time $t$ from the burst event approximately as (following Equations (56)–(57) in Metzger et al. 2019)

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

(1)

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

(2)
where $t_{\text{FRB}} \approx 10^{-3}$ s, which is a fiducial parameter and can be set to the observed duration of the burst. The peak synchrotron frequency cascades down to the synchrotron cooling frequency ($\nu_c$), which depends on properties of the circumburst material. Motivated by constraints on the engine of FRB121102 (Margalit & Metzger 2018), Metzger et al. (2019) considered previously ejected baryonic shells as the circumburst material, and parameterized $\nu_c$ in terms of the velocity of the ejected material ($\beta = \nu/c$), the average rate at which this material is injected into the surrounding medium ($M$), and the characteristic time between ejection events ($\Delta T$). Following Equation (60) in Metzger et al. (2019), the cooling frequency is

\[
\nu_c = 9 \text{ keV} \left( \frac{\sigma}{0.1} \right)^{-3/2} \left( \frac{\beta}{0.5} \right)^3 \left( \frac{M}{10^{21} \text{ g s}^{-1}} \right)^{-1} \left( \frac{t}{10^{-3} \text{ s}} \right)^{-1/2} \left( \frac{\Delta T}{10^5 \text{ s}} \right)^2.
\]  

(3)

Critically, the average period $\Delta T$ between bursts, although directly observable and constrained for FRB 180916 as 16.3 days (CHIME/FRB Collaboration et al. 2020b), simply depends on the circumburst density under the assumption that the surrounding medium is filled by ions from previous mass ejection events. In Equation (3), we assume that this medium is characterized by a series of discrete ion shells with a number density of ions in the surrounding medium $n_{\text{ext}} \propto (\Delta T)^{-2}$ where the density profile with radius $r$ from the source of the burst is $n_{\text{ext}} \propto r^{-k}$. For the discrete shells case, we adopt a $k = 0$ following the prescription in Margalit et al. (2020b).

The $k = 0$ profile provides a natural model for the environment of a source with episodic ejections, but this profile may not accurately describe the local environment around FRB progenitor systems if they erupt inside of a steady wind ($k = 2$), a low-density, ambient medium, or homologously expanding shells of ejecta from a supernova. In general, these environments would imply a much lower circumburst density at the shock radius where we observe optical emission, in which case our observations would be less constraining for similar values of $E_{\text{flare}}$. This is important for associating properties of the radio burst itself with optical emission on the timescale of our observations because the radio and optical data probe different timescales and thus different radii from the progenitor system. We characterize the radius of the radially expanding plasma as $r_{\text{FRB}} \approx 2T^2 c t \approx (10^{12} - 10^{13}) \text{ cm}$ for the radio burst with $t_{\text{FRB}} = 10^{-3}$ s and a Lorentz factor $\Gamma$; Metzger et al. 2019; Margalit et al. 2020b). Below we assume that the $k = 0$ density profile continues outward for several decades in distance such that the synchrotron maser light curve holds up to $t_{\text{syn}} \gg t_{\text{burst}}$ when the FRB is emitted (see Equation (7) below). This assumption may hold true if the medium is filled via the continuous ejection of material from a magnetar, but it is a caveat to the following analysis.

Throughout the rest of this Letter, we transform $\Delta T$ in (i.e., in Equation (3)) to $n_{\text{ext}}$, representing the circumburst density at a radius from the progenitor $r_{\text{FRB}} = 2T^2 c t_{\text{FRB}}$, following Equation (32) in Metzger et al. (2019) such that

\[
\nu_c = 2.3 \text{ keV} \left( \frac{\sigma}{0.1} \right)^{-3/2} \left( \frac{n_{\text{ext}}}{10^6 \text{ cm}^{-3}} \right)^{-1} \left( \frac{t}{10^{-3} \text{ s}} \right)^{-1/2}.
\]  

(4)

We predict that the light curve will peak roughly on the timescale when the peak synchrotron frequency $\nu_{\text{syn}}$ drops below the observing frequency ($\approx 3.6 - 7.5 \times 10^{14}$ Hz for $gri$), at which point we assume an exponential decline in optical luminosity. We include this cutoff in our light curves by rescaling the optical luminosity by $\exp(-t/(\nu/\nu_{\text{syn}} - 1))$ when $\nu > \nu_{\text{syn}}$. Overall, we use Equations (63)–(64) in Metzger et al. (2019) to model the peak luminosity ($L_{\text{pk}}$) and specific luminosity ($L_{\nu}$) of the optical light curve at $t > t_{\text{FRB}}$ as

\[
L_{\text{pk}} = 10^{45} \text{ erg s}^{-1} \left( \frac{E_{\text{flare}}}{10^{43} \text{ erg}} \right) \left( \frac{t}{10^{-3} \text{ s}} \right)^{-1}
\]  

(5)

\[
\nu L_{\nu} = \begin{cases} L_{\text{pk}} \left( \frac{\nu}{\nu_{\text{syn}}} \right)^{1/3} \left( \frac{\nu_c}{\nu_{\text{syn}}} \right)^{1/2}, & \nu < \nu_c \\ L_{\text{pk}} \left( \frac{\nu}{\nu_{\text{syn}}} \right)^{1/2}, & \nu_c < \nu < \nu_{\text{syn}}. \end{cases}
\]  

(6)

We note that in Figure 2 the light curve begins to decline when $\nu = \nu_{\text{syn}}$, which occurs at

\[
t_{\text{syn}} = 82.6 \text{ s} \left( \frac{\lambda}{5000 \text{ Å}} \right)^{2/3} \left( \frac{\sigma}{0.1} \right)^{1/3} \left( \frac{E_{\text{flare}}}{10^{43} \text{ erg}} \right)^{1/3}
\]  

(7)

where $\lambda$ is the observed wavelength. Thus for $r$-band ($\approx 6231$ Å), the timescale for $E_{\text{flare}} = 10^{45}$ erg and $\sigma = 0.3$ (as in Metzger et al. 2019) is $\approx 640$ s, or about one-third of our observation window. This is also significantly longer than any individual observation, implying that our limits for the full set or some subset of our observations are much more constraining than limits from individual exposures.

Moreover, the predicted luminosity is comparable to or brighter than our limits in the $10^{45}$ erg case, with the peak occurring around this time at $\nu L_{\nu} = 8 \times 10^{40}$ erg s$^{-1}$. We also note that higher densities will result in significantly more luminous bursts with $\nu L_{\nu} \propto n_{\text{ext}}^{3/k}$ as we are always in the regime where the optical frequency is below the cooling frequency.

Assuming the synchrotron maser model with the same fiducial parameters given above, we consider varying the energy scale of the burst $\log(E_{\text{flare}}/\text{erg}) \in [41.2, 47.4]$ and circumburst ion density $\log(n_{\text{ext}}/\text{cm}^{-3}) \in [1, 6.2]$ (which encompasses the full range of parameters for bursts considered in Margalit et al. 2020b). We then model the total in-band emission for our $gri$ observations by calculating the average specific luminosity integrated over the time of each observation relative to the burst arrival time and averaged over frequencies corresponding to the filter response function. We convert this value to a predicted apparent magnitude assuming the distance modulus and foreground extinction given above. For each model in our grid, if the computed apparent magnitude is brighter than any of our $3\sigma$ limiting magnitudes given in Table 1 (including the $3\sigma$ limits for the stacked, post-burst imaging), we consider that model ruled out as shown through the grayed-out region from Figure 3.

This model assumes that both the circumburst and interstellar host extinction are negligible in the context of likely optical counterparts. In an ion-rich medium the optical depth would be dominated by electron scattering with $\tau \approx 10^{-7}$ following Equation (33) in Metzger et al. (2019).

The interstellar burst host extinction could be dominated by dust with no indication in the radio signal, and indeed, FRB 180916 appears coincident with a small enhancement in
Figure 3. Flare energy ($E_{\text{flare}}$) and circumburst density ($n_{\text{ext}}$) parameter space for FRBs for Metzger et al. (2019) synchrotron light curves as described in Section 3. We show the range inferred for individual bursts as error bars (from Margalit et al. 2020b, 2020a) and FRB 180916 bursts shown in red. We demonstrate the energy-density parameter range that we can rule out for the 2020 September 3 burst of FRB 180916 and using our optical limits as a gray region.

The optical emission from its host galaxy (Marcote et al. 2020; Tendulkar et al. 2020). This finding suggests that FRB 180916 is located within or near a star-forming region (it is 250 pc from a young stellar clump based on a H$\alpha$ detection in Hubble Space Telescope imaging; Tendulkar et al. 2020) where there could be excess gas and dust obscuring the optical counterpart (similar to, e.g., stripped-envelope supernovae, which evolve from very massive, young stars and thus are observed with high average interstellar host extinction near their birth environments; Stritzinger et al. 2018).

A constraint on the total extinction in the FRB 180916 host galaxy comes from the DM observed toward this source, which is known to be on average $\approx$350 pc cm$^{-3}$ and 352.6 $\pm$ 3.2 pc cm$^{-3}$ for the 2020 September 3 burst. From this value, we account for Milky Way interstellar dispersion adopting 171.7 pc cm$^{-3}$ on the line of sight toward FRB 180916 (using the NE2001 model of Cordes & Lazio 2002), although this value is uncertain by $\approx$30%. In addition, the Milky Way halo adds a DM of 50 pc cm$^{-3}$, but it may range from 30 to 80 pc cm$^{-3}$ (e.g. Prochaska & Zheng 2019; Platts et al. 2020). To account for the intergalactic DM, we adopt the relation in Macquart et al. (2020) at $z = 0.0337$, which gives 56 $\pm$ 20 pc cm$^{-3}$. Multiplying the residual DM by 1 + $z$, we obtain a source-frame DM host-galaxy contribution in the line of sight to FRB 180916 of 75 $\pm$ 70 pc cm$^{-3}$. This is equivalent to a hydrogen column density of $N_{\text{H}} = 2.3 \pm 2.1 \times 10^{21}$ cm$^{-2}$ following the locally derived relation in He et al. (2013). Finally, this column yields $A_V \approx 1.0 \pm 0.9$ mag following Güver & Özel (2009). Clearly this value has significant systematic uncertainty and may be consistent with effectively zero host extinction. Fitting the dust content in the FRB 180916 host yields a much lower dust content of $E(B - V) = 0.12$ mag (Heintz et al. 2020), which implies $A_V = 0.4$ mag assuming $R_V = 3.1$. Although this value is not a line-of-sight probe similar to the DM, it is nominally consistent with the lower bound of our interstellar host extinction estimate. Therefore, we conservatively adopt $A_V = 0.50$ mag with $R_V = 3.1$ to model our observations below and assume a Cardelli et al. (1989) reddening relation, implying that $A_g = 0.53$ mag, $A_r = 0.37$ mag, and $A_i = 0.27$ mag due to interstellar dust in the host of FRB 180916.

To place our final limiting magnitudes in context, we consider the full range of circumburst densities corresponding to FRB 180916 in Margalit et al. (2020b). In general, the energy of the burst $E_{\text{flare}}$ can be estimated from the equivalent isotropic energy in a single radio burst ($E_{\text{radio}}$) following Margalit et al. (2020a, 2020b) as

$$\frac{E_{\text{radio}}}{E_{\text{flare}}} \approx 8.6 \times 10^{-3} f_r \frac{\nu_{\text{obs}}}{\nu_{\text{radio}}} \left(\frac{f_r}{10^3}\right)^{-1/5}$$

where the observation frequency $\nu_{\text{obs}}$ and the total burst duration $t_{\text{FRB}}$ are known from radio observations, the ratio of electron to ion number densities in the upstream medium $f_r = 0.5$ is assumed, and the synchrotron maser efficiency is $f_r \approx 10^{-3}$ (Plotnikov & Sironi 2019). We do not currently know the fluence ($S_r$) or duration of the 2020 September 3 radio burst from FRB 180916, and so we assume that it followed the distribution from CHIME/FRB Collaboration et al. (2020b), with $E_{\text{radio}} = 4\pi D^2 t_{\text{eff}} S_r$ at 400 MHz of $(1.1-39.8) \times 10^{37}$ erg and $t_{\text{FRB}}$ of $\approx$0.6-8.6 ms (corresponding to $E_{\text{flare}} = 0.04-1.45 \times 10^{43}$ erg based on the formalism in Margalit et al. 2020b). Assuming an average $E_{\text{radio}} = 6.8 \times 10^{37}$ erg and $t_{\text{FRB}} = 3.7$ ms for bursts with well-measured fluence and duration in CHIME/FRB Collaboration et al. (2020b), we estimate that the average energy per burst is $E_{\text{flare}} = 2.5 \times 10^{42}$ erg for FRB 180916 as shown in Figure 3.

This places the average optical counterpart well outside the range of detectability for our observations and the model parameters above (noting the grayed-out region in Figure 3 and assuming FRB 180916 parameters—red error bars—from Margalit et al. 2020b). The burst parameters inside the grayed-out region correspond to five different localized sources in Margalit et al. (2020b), specifically FRB 121102, 180814, 180924, 181017, and 190523. From the expected moment of dispersion-corrected burst arrival at optical wavelengths, the timescale for an optical light curve with $E_{\text{flare}} = 2.5 \times 10^{42}$ erg and $\sigma = 0.3$ is $t_{\text{syn}} \approx 87$ s, implying that most of our imaging after this point is not very constraining in the context of likely optical counterparts.

Moreover, for a circumburst density $n_{\text{ext}} = 2000$ pc cm$^{-3}$ (roughly the median value for FRB 180916 in Margalit et al. 2020b), the burst would have an optical luminosity $L_{V_{\text{opt}}} = 6 \times 10^{38}$ erg s$^{-1}$ ($M \approx -8$ mag or $m \approx 28$ mag at 150 Mpc) on the timescale $t_{\text{syn}}$. This is below the threshold of detectability for nearly all optical telescopes, even assuming infinite integration time. For high-speed optical imagers that can observe on the timescale of tens of ms around a burst (e.g., the 2.4 m Thai National Telescope/ULTRASPEC with $m_{\text{lim}} = 16.8$ mag over 70 ms; Hardy et al. 2017), the detection threshold is shallower by several orders of magnitude. Thus to detect a burst at optical wavelengths with a light curve similar to those above, a large-aperture telescope and an anomalously energetic burst with $E_{\text{flare}} > 10^{44}$ erg would be needed (following our limits and the maximum densities inferred for FRB 180916 in Figure 3).
On the other hand, if the source were in a highly active state with significantly larger energies and shorter timescale between bursts, this might boost the circumburst density and the corresponding optical signal and potentially place the counterpart within the range of detectability. The shortest timescales between bursts for FRB 180916 are only 0.5 ms (observed on 2019 December 19; CHIME/FRB Collaboration et al. 2020b), or ≈100 s in cases where \( \Delta T/\Delta T \approx 1 \). Taking \( \Delta T = 100–1.4 \times 10^6 \) s as the full range of burst periods and assuming an extremely energetic burst with \( E_{\text{flare}} \approx 10^{54} \) erg, the circumburst density might exceed \( 10^6 \) cm\(^{-3} \) (as with FRB 121102, the burst with the highest inferred circumburst density in Margalit et al. 2020b). Based on the assumed \( n_{\text{ext}} \propto \Delta T^{-2} \) and \( L_{\text{pk}} \propto n_{\text{ext}}^{7/6} \) scaling above, this would require a change in average period of at least a factor of 5 or \( \Delta T \approx 3.3 \) days.

The FRB may have outbursts on timescales significantly shorter than 3.3 days (CHIME/FRB Collaboration et al. 2020b), although it is unclear whether these bursts would have similar flare energies or lead to a significantly denser circumburst medium in the magnetar-driven synchrotron maser model that we adopt above. Moreover, the \( k = 0 \) density profile discussed above may not be representative at all projected radii if the burst properties change significantly with time.

Thus, while it is unclear if FRB 180916 can briefly enter the parameter range we rule out in Figure 3, we would only require moderately deeper imaging or more frequent and energetic bursts to detect the optical counterpart. Finally, detailed analysis of the 2020 September 3 radio burst detected by CHIME will provide a direct constraint on the circumburst density (following Equation (8) in Margalit et al. 2020b).

For future optical follow-up efforts, this implies that in the context of the baryonic-shell version of the synchrotron maser model, the most promising search strategies will be to target FRB 180916 with a 8–10 m telescopes when it is in an active state and likely to have one or more bursts. On the other hand, if the burst profile is significantly more luminous on short timescales after the burst (e.g., following the models of Beloborodov 2020), high-speed cameras such as ULTRASPEC (Hardy et al. 2017) on large-aperture telescopes will yield the strongest constraints on potential optical counterparts. Moreover, if the burst period decreases and the circumburst density is temporarily enhanced, the optical counterpart may be bright such that prompt and/or long-lived counterparts are detectable.

### 4. Conclusions

We presented APO 3.5 m/ARCTIC observations of FRB 180916 around the time of a fast radio burst. Comparing to models of synchrotron maser emission corresponding to the broadband, relatively long-lived counterpart to a radio burst, we find the following.

1. Our observations are constraining for synchrotron maser emission in cases where the energy per burst is larger than \( \approx 10^{44} \) erg and the circumburst density is greater than \( 10^6 \) cm\(^{-3} \).
2. Comparing to previous constraints on the FRB 180916 burst energy from Margalit et al. (2020b), our limits are not constraining for the predicted burst parameters. However, if the circumburst density is temporarily enhanced when the FRB progenitor is highly active and multiple discrete bursts occur (e.g., on 2019 December 19 and 2020 February 4; CHIME/FRB Collaboration et al. 2020b), the predicted optical light curve could exceed the magnitude limit achievable by large-aperture telescopes.

We thank J.X. Prochaska for helpful comments on this manuscript. C.D.K. acknowledges support through a NASA grant in support of the Hubble Space Telescope program AR-16136. K.E.H. acknowledges support by a Project Grant (162948–051) from The Icelandic Research Fund. W.F. acknowledges support by the National Science Foundation under grant Nos. AST-1814782 and AST-1909358. B.M. is supported by NASA through the NASA Hubble Fellowship grant #HST-HF2-51412.001-A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. Based on observations obtained with the Apache Point Observatory 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium.

### Facilities

- APO 3.5 m (ARCTIC).

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