Constraining a neutron star merger origin for localized fast radio bursts

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ABSTRACT

What the progenitors of fast radio bursts (FRBs) are, and whether there are multiple types of progenitors are open questions. The advent of localized FRBs with host galaxy redshifts allows the various emission models to be directly tested for the first time. Given the recent localizations of two non-repeating FRBs (FRB 180924 and FRB 190523), we discuss a selection of FRB emission models and demonstrate how we can place constraints on key model parameters like the magnetic field strength and age of the putative FRB-emitting neutron star. In particular, we focus on models related to compact binary merger events involving at least one neutron star, motivated by commonalities between the host galaxies of the FRBs and the hosts of such merger events/short gamma-ray bursts (SGRBs). We rule out the possibility that either FRB was produced during the final inspiral stage of a merging binary system. Where possible, we predict the light curve of electromagnetic emission associated with a given model and use it to recommend multi-wavelength follow-up strategies that may help confirm or rule out models for future FRBs. In addition, we conduct a targeted sub-threshold search in Fermi Gamma-ray Burst Monitor data for potential SGRB candidates associated with either FRB, and show what a non-detection means for relevant models. The methodology presented in this study may be easily applied to future localized FRBs, and adapted to sources with possibly core-collapse supernova progenitors, to help constrain potential models for the FRB population at large.

Key words: radiation mechanisms: non-thermal – stars: neutron – stars: magnetars – radio continuum: transients – gamma-rays: general.

1 INTRODUCTION

Fast radio bursts (FRBs) are bright, extragalactic, (sub-)millisecond duration radio flashes of unknown origin (Lorimer et al. 2007; Thornton et al. 2013). Most FRBs are observed to be single events, despite many hours of follow-up observations (Petroff et al. 2015). Lack of repetition challenges our ability to localize them precisely, which would provide vital clues in understanding their elusive progenitors. Even repeating FRBs can be challenging to localize given their sporadic activity (CHIME/FRB Collaboration et al. 2019a). The precise localization of a large sample of repeating and non-repeating FRB sources is required to address the central question of whether there are multiple origins and, as a by-product, whether or not all FRB sources are intrinsically repeaters.

There is a long list of FRB origin theories and an overview is provided in Platts et al. (2019)1. Most viable repeating FRB models, though, involve a neutron star (NS) that is either magnetically or rotationally powered. The observation of repeat bursts from about 20 percent of known FRB sources (CHIME/FRB Collaboration et al. 2019b; Fonseca et al. 2020) raises the possibility of multiple FRB origins. Alternatively, all FRBs may repeat but their observable repeat may vary from one source to another depending on their environment or intrinsic bursting rate. Indeed, the high FRB rate compared to the rate of possible progenitors likely implies that the majority of FRB sources repeat (Ravi 2019). In any case, the contrast between the environments of repeating and (observed) non-repeating sources lends support to the possibility of multiple progenitors. Additionally, the characteristic of downward drifting sub-bursts in frequency, revealed in some repeat bursts of most repeat-

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ing sources, has yet to be observed in a one-off FRB (Hessels et al. 2019; CHIME/FRB Collaboration et al. 2019b; Fonseca et al. 2020). This burst morphology may serve as another diagnostic to distinguish between (observed) non-repeating and repeating FRB sources.

FRB 121102 (Spitler et al. 2014), the most active repeating source (Spitler et al. 2016), was the first FRB to be precisely localized, thanks to very long baseline interferometry (Chatterjee et al. 2017; Marcote et al. 2017). It was associated with a low-metallicity dwarf galaxy at redshift \( z = 0.19 \) (Tendulkar et al. 2017), in a region of active star formation (Basu et al. 2017; Kokubo et al. 2017), and coincident with a persistent radio source \( (1.8 \times 10^{30} \text{erg s}^{-1} \text{Hz}^{-1}) \), Chatterjee et al. 2017; Marcote et al. 2017). Furthermore, the bursts exhibit an enormous and variable rotation measure \( (\text{RM} \sim 10^5 \text{rad m}^{-2}) \), placing them in an extreme magnetized environment (Michilli et al. 2018). The host galaxy of FRB 121102 shares similar properties with the environments of long gamma-ray bursts (LGRBs) and type Ibc supernovae (Tendulkar et al. 2017; Marcote et al. 2017), which have massive star progenitors. A related interpretation is that the persistent radio source is a nebula powered by a magnetar, supplying a highly magnetized plasma (e.g. Murase et al. 2016; Beloborodov 2017; Metzger et al. 2017; Nicholl et al. 2017). Alternatively, the large RM and persistent radio emission may be due to an AGN in the vicinity of the bursting source (e.g. Marcote et al. 2017; Michilli et al. 2018; Zhang 2018).

A second repeater, FRB 180916.J0158+65, was localized by Marcote et al. (2020) to an outer arm of a nearby spiral galaxy in a star-forming region. Unlike FRB 121102, there is no comparably bright persistent radio source nor significant Faraday rotation. This result indicates that sources of repeat FRBs may reside in a variety of galaxy types and environments.

In 2019 August, the localizations of two non-repeating FRBs were reported. FRB 180924 was localized to milliarcsecond precision and, unlike FRB 121102 and FRB 180916.J0158+65, repeat bursts have not been detected from this source in approximately 11 hours of follow-up observations conducted over two separate observing sessions separated by two weeks (Bannister et al. 2019). The host galaxy of FRB 180924 is markedly different from the environment of FRB 121102. Namely, the host is a spiral galaxy \( (z = 0.32) \) with limited star formation, there is no persistent source of radio emission above \( 7 \times 10^{28} \text{erg s}^{-1} \text{Hz}^{-1} \), and the burst has a negligible RM of \( 14 \text{ rad m}^{-2} \) (Bannister et al. 2019). The other source, FRB 190523, was localized with arcsecond accuracy to a massive galaxy at \( z = 0.66 \) with limited star formation activity \( (< 1.3 M_\odot \text{ yr}^{-1}) \) (Ravi et al. 2019). There is no associated constant radio emission greater than \( 7 \times 10^{30} \text{erg s}^{-1} \text{Hz}^{-1} \). Polarietric information is not available for this source. No repeat bursts were observed in 78 hours of follow-up observations conducted within a span of 54 days. The environments of these localized sources both have low star formation rates, which contrasts the active star formation regions associated with the only two localized repeating sources\(^2\).

Interestingly, both FRB 180924 and FRB 190523 were emitted in the outskirts of their host galaxy. The limited star formation (pointing to an older stellar population) and position offset from their hosts are consistent with a neutron star merger origin (binary neutron star, BNS, or black hole neutron star, BHNS). Margalit et al. (2019) and Wang et al. (2020) show that the environments of FRB 180924 and FRB 190523 are consistent with the population of SGRBs, which are produced during BNS and possibly BHNS mergers. Comparisons between the rates of FRBs and neutron star mergers show that only a fraction of non-repeating FRBs could be produced via BNS or BHNS mergers, but that if most or all FRBs repeat on sufficiently long timescales, the rates are adequate for FRBs to emanate from neutron stars born out of BNS mergers (Cao et al. 2018; Ravi 2019; Margalit et al. 2019; Wang et al. 2020).

In this paper, we explore the scenario in which FRB 180924 and FRB 190523 are associated with a compact binary merger involving at least one neutron star. We consider six models (some capable of producing repeat bursts) within the BNS and BHNS merger scenarios and place limits on key parameters within each model using the observed properties of both FRBs. Where applicable, we demonstrate the value of multi-wavelength data sets. In addition, we perform targeted searches for associated SGRBs in Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) data. We emphasize that most of the models we present can be adapted to FRBs related to core-collapse supernovae. In §2, we describe the models being considered and in §3 we demonstrate our SGRB search. We present and discuss our results for each model in §4 and draw our main conclusions in §5.

2 RELEVANT FRB MODELS

In this section, we provide an overview of the FRB models we have chosen to examine using the measured parameters of FRB 180924 and FRB 190523. The models are organized by the merger stage in which they are expected to occur. We consistently use the following definition for FRB luminosity, unless stated otherwise:

\[
L_{\text{FRB}} = \Omega F_\nu \Delta \nu D^2,
\]

where \( \Omega \) is the solid angle illuminated by the beam of emission \( (0 < \Omega \leq 4\pi) \), \( F_\nu \) is the flux measured across the observing frequency bandwidth, \( \Delta \nu \), and \( D \) is the luminosity distance. We implicitly assume a flat spectrum across the observing bandwidth. In using \( \Delta \nu \) as opposed to, for example, the observing frequency, we make no assumption about the breadth of the intrinsic spectrum of emission. However, we are likely underestimating the luminosity in this way, since the emission of both FRBs is presumably detectable beyond the observing bandwidth, though to unknown extents (see Gourdji et al. 2019). We shall comment on the impact this has on the models in the sections that follow.

\(^2\) A third source of a singular FRB was more recently localized by Prochaska et al. (2019), bringing the total of localized sources to five (2 repeating and 3 non-repeating).
2.1 Pre-merger

If at least one neutron star is magnetized in an inspiralling compact binary system, as the companion (BH or NS) moves through the magnetosphere of the charged neutron star, a current may be driven through the magnetic field lines that connect the system, like a battery. This surge accelerates charged particles along the field lines and electromagnetic (EM) emission may be produced. The total “battery” power available for extraction into electromagnetic emission increases as the orbital separation decreases and orbital velocity increases, and so the emission may only be detectable during the final stages of the inspiral. The emission is expected to peak at the point of contact (or point of tidal disruption) of the binary system. Either hemisphere of the conducting companion forms a closed circuit with either magnetic pole of the primary neutron star. The voltage induced along the magnetic field lines can be expressed as (McWilliams & Levin 2011; Piro 2012; D’Orazio et al. 2016)

\[ \oint (\frac{\mathbf{v}}{c} \times \mathbf{B}) \cdot d\mathbf{l}, \]  

(2)

where \( \mathbf{B} \) is the magnetic field vector, \( d\mathbf{l} \) is the segment that contributes to the electromotive force, \( \mathbf{v} \) is the relative orbital velocity of the conducting companion (neglecting the magnetized neutron star’s rotation) and \( c \) is the speed of light. Due to the dot product, only those segments parallel to the induced electric field contribute \( (2\mathbf{R}) \).

The potential difference, \( V(r) \), across one hemisphere of the conducting companion is then

\[ V(r) = 2 R \frac{v}{c} B \left( \frac{R_{\text{NS}}}{r} \right)^3, \]

(3)

where \( r \) is the orbital separation, \( R \) is the radius of the conducting companion, \( R_{\text{NS}} \) is the radius of the primary neutron star, and the last term comes from the fact that the strength of the magnetic field drops off as the distance cubed. The total battery power from both hemispheres is then

\[ P = 2 \frac{V^2}{r^2}, \]

(4)

where \( R \) is the resistance of the system. The resistance across the horizon of a black hole is \( \frac{4\pi}{c} \) (impedance of free space, Znajek 1978). The resistance across a neutron star’s magnetosphere is less obvious, but can at most reduce the total power by approximately one half, so we therefore neglect it from our analysis for simplicity (see McWilliams & Levin 2011 for discussion).

In a BNS system, the BH (out to horizon radius \( R_{\text{H}} = \frac{3GM}{c^2} \)) is the conductor that induces the electromagnetic force along the NS’s field lines as it orbits through them (e.g. Mingarelli et al. 2015). The total battery power available for conversion into radio emission increases as the orbital separation decreases. We consider the maximal energy case, where the closest orbital separation is the photon sphere radius, \( r = \frac{3GM}{c^2} \) (note that this is \( \frac{GM}{c^2} \) for a spinning BH). The resulting power is then (combining equations 3 and 4)

\[ P = \frac{8c^3}{27\pi} \left( \frac{GM}{c^2} \right)^{-4} B^2 R_{\text{NS}}^2 \frac{v^2}{c^2}. \]

(5)

We take \( \frac{c}{v} \approx 1 \) for simplicity, take the mass of the black hole

to be \( 10 M_\odot \), and \( R_{\text{NS}} = 10 \text{ km} \). Solving equation 5, we end up with battery radio luminosity

\[ L = 2 \times 10^{45} \left( \frac{B}{10^{13} \text{ G}} \right)^2 \epsilon_r \text{ erg s}^{-1}, \]

(6)

where some fraction \( \epsilon_r \) of the total battery power available is converted into radio emission, depending on the method of energy extraction. We caution that there are caveats to using both smaller and larger BH masses, as the equations may no longer be appropriate (NS plunging into the BH versus tidal disruption). These are addressed in McWilliams & Levin (2011) and D’Orazio et al. (2016).

For a binary neutron star system, equation 3 is used with \( v = \omega r \), where \( \omega = \frac{\sqrt{2GM}}{r} \) is the orbital frequency (we neglect contribution to \( V \) from the neutron star spin) (Metzger & Zivancev 2016). Using \( R = \frac{\epsilon}{\epsilon_x} \) for the primary neutron star’s magnetosphere, and minimizing the orbital separation to the point of Roche contact \( (r = 2.6R, \text{ Eggleton 1983}) \), the total power available is then

\[ P = \frac{4GM^2 R^8}{cr^7 \pi} \]

(7)

Setting \( R = 10 \text{ km} \) and \( M = 1.4 M_\odot \), the radio luminosity can then be expressed as:

\[ L = 1 \times 10^{45} \left( \frac{B}{10^{13} \text{ G}} \right)^2 \epsilon_r \text{ erg s}^{-1}. \]

(8)

This idea of radio emission from inspiralling BNS systems has also been considered in Hansen & Lyutikov (2001) but with slight differences (in particular a more complex treatment of the electrodynamics) that amount to a larger derived maximum luminosity by almost an order of magnitude (also see Lyutikov 2013, equation 12). The model is revisited in Lyutikov (2019) with two magnetized neutron stars. Piro (2012) expanded on the BNS battery system, demonstrating the dissipation energy available as a function of time, and paying particular attention to the resistance of the circuit.

2.2 During a SGRB

If a GRB jet that is powered by a Poynting flux dominated wind is launched following a merger, radio emission may be generated at the shock front and detected as an FRB, if the radio waves can escape through it (Usov & Katz 2000). This mechanism requires a highly magnetized wind, which is assumed to come from a rapidly rotating and highly magnetized central engine (a neutron star or an accretion disk around a black hole). The magnetic field of the shock front between the wind and ambient medium, in the rest frame of the wind, is (Usov & Katz 2000):

\[ B_0 = \epsilon_B \frac{1}{B} \frac{R^3}{c} e^{-2} \left( \frac{2n}{P_0} \right)^2 Q^{-1} n^1 q^{-1}, \]

(9)

where \( \epsilon_B \) is the fraction of wind energy contained in the magnetic field, \( R \) is the radius of the compact object, \( P_0 \) is its initial spin period, \( B \) is the surface magnetic field of the disk or NS, \( n \) is the density of the ambient medium, \( Q \) is the kinetic energy of the wind assuming spherical outflow, and \( \Gamma \) is the Lorentz factor. We shall assume standard values \( B = 10^{14-16} \text{ G} \), \( R = 10^6 \text{ cm} \), \( P_0 = 1 - 10 \text{ ms} \), \( Q = 10^{53} \text{ ergs} \), \( \Gamma = 1000 \), \( n = 10^{-2} \text{ cm}^{-3} \). The peak radio emission frequency,
\( v_{\text{max}} \), is then the gyration frequency of an electron in a magnetic field \( B_0 \), which works out to \( v_{\text{max}} \approx \frac{eB_0}{\pi m_p} \) (Usov & Katz 2000, equation 5). In this model, we assume that the radio emission ranges from the gyration frequency to the observing frequency of the FRB. The bolometric radio fluence, \( \Phi_r \), is then:

\[
\Phi_r = \frac{\nu_{\text{FRB}}}{\nu_{\text{obs}}} (\alpha + 1) (\nu_{\text{obs}} - \nu_{\text{max}}) \tag{10}
\]

where \( \nu_{\text{FRB}} \) is the measured fluence of the FRB, \( \nu_{\text{obs}} \) is the observing frequency, and \( \alpha \) is the spectral index assumed to be \(-1.6\). According to Usov & Katz (2000), the bolometric gamma-ray fluence, \( \Phi_\gamma \), is related to \( \Phi_r \) as

\[
\frac{\Phi_r}{\Phi_\gamma} \approx 0.1eB \tag{11}
\]

Combining equations 10 and 11, one can solve for the expected gamma-ray fluence, \( \Phi_\gamma \approx eB R_0^2 B \). Given that the radio and gamma-ray emission arise from the same region, beaming effects should cancel in equation 11.

### 2.3 Post-merger

#### 2.3.1 Pulsar-like emission

If the merger remnant is a neutron star, it may be detectable through pulsar emission from its amplified magnetic field. A comparison to the energetics of the population of known radio pulsars will quickly reveal a disparity spanning several orders of magnitude relative to the energy of FRBs. Therefore, pulsar giant pulse emission (an observational term referring to pulses with fluence greater than some multiple, typically taken to be 10, of the average, Karuppusamy et al. 2010) has often been invoked in an effort to close this gap, in the rotationally powered pulsar model for FRBs. This is because giant pulses offer more freedom in the parameter space available. Specifically, one can say that giant pulses result from increases in efficiency and/or beaming. Following the model described in Pohirkov & Postnov (2010), it is assumed that the radio luminosity \( L \) is equal to some fraction of the energy loss rate of the magnetically driven outflow, \( |\dot{E}| \). Therefore, it follows that (using equation 1)

\[
L = \epsilon_r |\dot{E}|, \tag{12}
\]

for the predicted emission. In equation 12, \( \epsilon_r \) encapsulates all unknowns related to the emission mechanism and simply says that some fraction of the dipole energy is converted into the observed radio emission. The standard pulsar spin-down equation is ( Lorimer & Kramer 2004)

\[
\dot{E} = \frac{16\pi^2 B^2 R^6}{3 \overline{P} c^3}, \tag{13}
\]

where \( P \) is the spin period, \( B \) is the magnetic field at the surface of the neutron star and \( c \) is the speed of light. The angle between the magnetic moment and the spin axis is a source of uncertainty and depends on the physics of the NS magnetic field and EOS, but is thought to be near zero at the time of birth, and is expected to increase with time (e.g. Dall’Osso et al. 2009). We have therefore assumed a fiducial value of 30°, and note that a range from 1° (nearly aligned spin and magnetic axes) to 90° (orthogonal spin and magnetic axes) corresponds to about an order of magnitude difference for the derived NS magnetic field. Plugging \( \dot{E} \) from equation 13 into equation 12 and solving for \( B \), we find that its dependence on the three most uncertain quantities is \( B \propto \Omega^2 \overline{P}^2 e_r^{-\frac{1}{2}} \).

#### 2.3.2 Flaring magnetar

An alternative to rotational energy extraction is magnetically powered neutron star emission. A popular subclass is the flaring magnetar (Lyubarsky 2014; Beloborodov 2017; Metzger et al. 2019; Beloborodov 2020). In this scenario, giant flares, caused by instabilities in the magnetosphere, shock the plasma surrounding the magnetar to produce maser emission detectable at radio frequencies. In order to establish the relevant parameters, we outline and build on the model presented in Lyubarsky (2014). The various models diverge at different steps, but possibly the most important differences lie in the nature of the upstream/shocked material, which we address in §4.3.2.

The magnetar flares start in the form of magnetohydrodynamic waves (Alfvén waves) that propagate in the magnetosphere, sweeping up field lines to form a pulse that travels through the magnetar’s wind. The wind is composed of magnetized electron positron plasma and its luminosity is determined by the spin-down luminosity. The wind’s end boundary occurs when the wind’s bulk pressure is balanced by the pressure confining the wind. There is a termination shock at the radius at which this balance occurs, and a hot wind bubble (like a nebula) consequently forms. When the pulse reaches the termination shock, it meets a discontinuity as the upstream medium suddenly changes from the cold wind to the hot wind/nebula. It blasts the plasma in the nebula outward, generating a forward shock that propagates through the nebula’s plasma. The magnetic field of the wind runs perpendicular to the pulse and the shock is mediated by that field. The gyration of the shocked particles creates an unstable synchrotron maser, that produces low-frequency maser emission detectable at radio frequencies. In order to establish this model, we outline and build on the model presented in Lyubarsky (2014).

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#### 2.3.3 Curvature radiation

Apart from maser emission, which was explored in the previous section, particle energy may be dissipated through curvature radiation and detected as an FRB. Models where the
FRB is produced within the magnetosphere have the advantage of not having to deal with the potentially critical effects of induced Compton scattering, which lead to losses in photon energy (Lu & Kumar 2018). In the model presented by Kumar et al. (2017), particles are accelerated by an electric field parallel to the magnetar’s magnetic field lines. Based on this idea, Lu & Kumar (2019) show that the FRB luminosity is limited by the parallel electric field, $E_{||}$, which can be at most 5 per cent of the quantum critical field ($\frac{m_e c^2}{\hbar} = 4.4 \times 10^{13}$ esu) for electrons, Stebbins & Yoo (2015), else the electric field gets shielded by Schwinger pairs. The moving particles will induce a magnetic field, $B_{\text{ind}}$, perpendicular to the field lines. This induced field must not perturb the original magnetic field, $B$, by more than a factor of the beaming angle $\gamma^{-1}$, else coherence is lost. Applying the requirements that i) $E_{||} < 2.5 \times 10^{12}$ esu and ii) $B_{\text{ind}} < B\gamma^{-1}$, and following Lu & Kumar (2019), the following requirement on $B$ can be set:

$$B > \frac{(2\pi)^{2/3}L_{\text{iso}}^{2/3}}{E_{||}[\rho^{1/3}c^{2/3}]} \approx 6 \times 10^{12} G \left( \frac{L_{\text{iso}}}{10^{44} \text{erg s}^{-1}} \right) \left( \frac{\nu}{1.4 \text{GHz}} \right)^{2/3},$$

(15)

where $\rho$ is the curvature radius, taken to be $10^6$ cm (the local magnetic field may be too weak at larger values), and $\nu$ is the peak frequency of the emission, taken to be the central observing frequency of the FRB. The spectrum of the predicted emission is broadband.

2.3.4 Neutron star collapse

Here, we entertain the scenario where the post-merger product is a neutron star that collapses at some point into a black hole. During this process, the neutron star ejects its magnetosphere (according to black hole no-hair theorem) emitting a short duration burst of coherent radio emission (Falcke & Rezzolla 2014). Zhang (2014) estimate that the total amount of magnetic energy $E_B$ stored in the magnetar’s magnetosphere is approximately $\frac{1}{3} B^2 R^3$, of which some fraction $\epsilon_{\nu}$ is converted into coherent radio emission. The radio luminosity is then

$$L = \epsilon_{\nu} \frac{E_B}{\Delta t} = \epsilon_{\nu} \frac{B^2 R^3}{6\Delta t}.$$  

(16)

Rearranging equation 16 and using equation 1, we can solve for the magnetic field at the surface of the collapsing merger remnant,

$$B = \frac{6F_{\nu}OD^2\Delta t\Delta \nu}{\epsilon_{\nu} R^3} \frac{1}{2}.$$  

(17)

3 SEARCH FOR SGRB COUNTERPARTS

All FRB models in this study should theoretically have a SGRB counterpart. The expected amount of time elapsed between the SGRB and FRB detections is model dependent and can range from decades (§4.3.2) after the SGRB to seconds before the SGRB (§4.1). Margalit et al. (2019) checked archival data for positionally coincident SGRBs that could be associated with FRB 180924. Given the lack of positional accuracy of most GRB detectors, there are naturally several possible associations over the last decades. We perform the same check for FRB 190523 using the Swift/BAT catalogue as it provides by far the best positional accuracy (on average a positional error radius of only 1.6′). An association was not found, though the instrument’s instantaneous field of view is roughly only 15 per cent of the sky and could therefore conceivably miss a GRB counterpart to an FRB.

The Fermi GBM, however, sees about 65 per cent of the sky. Therefore, to test the possibility of detecting a temporarily coincident GRB counterpart, we study the data from the Fermi GBM during a window of 30 minutes prior to and 1 minute after the FRB detections. In order to find any signal that may be too weak to trigger the detectors on-board the spacecraft, and to set the most stringent flux upper limits in the absence of any such signal, we utilize the Fermi targeted sub-threshold search that was developed to search for short GRB counterparts to gravitational-wave signals (Blackburn et al. 2015; Goldstein et al. 2019; Hamburg et al. 2020). The targeted sub-threshold search operates by performing a spectrally and detector-coherent search of the GBM data around a time window of interest, and it has been validated by showing that it can recover GRBs detected by the Swift BAT, but that were at unfavorable arrival geometries or too weak to trigger the onboard detection algorithms (Kocevski et al. 2018). In addition to gravitational-wave follow-up (Burns et al. 2019), the targeted search has been utilized to search for short GRB counterparts to astrophysical neutrinos (e.g.; Veres 2019; Wood 2019) and to other FRBs (Cunningham et al. 2019).

Operating the GBM targeted search during the (-30, +1) minute window around each FRB, we find that while GBM was able to observe the location of FRB 190523 during the full window, unfortunately the location of FRB 180924 was only visible until ∼26 minutes prior and then was occulted by the Earth for the remainder of the window. The targeted search did not find any promising candidates, however we can place time-dependent coherent flux upper limits for the known positions of the FRBs, which is shown in Figure 1. For a signal with duration between 0.1 s and 1 s in the 50–350 keV band, the $4.5\sigma$ flux upper limits are typically below $~10^{-6}$ erg s$^{-1}$ cm$^{-2}$, with time-dependent variations that span more than an order of magnitude as a result of the spacecraft orbital and pointing motion relative to the source positions. Additionally, for comparison, we estimate the flux upper limit for a single GBM detector observing the FRB position at an angle of 70° to the detector boresight, which is a good proxy for a very poor observing scenario for a single GRB scintillation detector. This is done by choosing a few random intervals in a single detector during the 31-minute period considered in the search. For each interval, a local background is fit, a detector response is generated assuming a source angle of 70° from the detector boresight, and the spectral amplitude for the same spectrum used in the targeted search is fit to the data above background. From the assumed spectrum and fitted amplitude, we estimate the corresponding flux upper limit. We find this upper limit to be $~10^{-6}$ erg s$^{-1}$ cm$^{-2}$ for a 1-s duration signal, and the variance of this upper limit shown in Figure 1 is from the range of upper limits calculated from the chosen random intervals.

Margalit et al. (2019) checked archival data for positionally coincident SGRBs that could be associated with FRB 180924. Given the lack of positional accuracy of most GRB detectors, there are naturally several possible associations over the last decades. We perform the same check for FRB 190523 using the Swift/BAT catalogue as it provides by far the best positional accuracy (on average a positional error radius of only 1.6′). An association was not found, though the instrument’s instantaneous field of view is roughly only 15 per cent of the sky and could therefore conceivably miss a GRB counterpart to an FRB.

The Fermi GBM, however, sees about 65 per cent of the sky. Therefore, to test the possibility of detecting a temporarily coincident GRB counterpart, we study the data from the Fermi GBM during a window of 30 minutes prior to and 1 minute after the FRB detections. In order to find any signal that may be too weak to trigger the detectors on-board the spacecraft, and to set the most stringent flux upper limits in the absence of any such signal, we utilize the Fermi targeted sub-threshold search that was developed to search for short GRB counterparts to gravitational-wave signals (Blackburn et al. 2015; Goldstein et al. 2019; Hamburg et al. 2020). The targeted sub-threshold search operates by performing a spectrally and detector-coherent search of the GBM data around a time window of interest, and it has been validated by showing that it can recover GRBs detected by the Swift BAT, but that were at unfavorable arrival geometries or too weak to trigger the onboard detection algorithms (Kocevski et al. 2018). In addition to gravitational-wave follow-up (Burns et al. 2019), the targeted search has been utilized to search for short GRB counterparts to astrophysical neutrinos (e.g.; Veres 2019; Wood 2019) and to other FRBs (Cunningham et al. 2019).

Operating the GBM targeted search during the (-30, +1) minute window around each FRB, we find that while GBM was able to observe the location of FRB 190523 during the full window, unfortunately the location of FRB 180924 was only visible until ∼26 minutes prior and then was occulted by the Earth for the remainder of the window. The targeted search did not find any promising candidates, however we can place time-dependent coherent flux upper limits for the known positions of the FRBs, which is shown in Figure 1. For a signal with duration between 0.1 s and 1 s in the 50–350 keV band, the $4.5\sigma$ flux upper limits are typically below $~10^{-6}$ erg s$^{-1}$ cm$^{-2}$, with time-dependent variations that span more than an order of magnitude as a result of the spacecraft orbital and pointing motion relative to the source positions. Additionally, for comparison, we estimate the flux upper limit for a single GBM detector observing the FRB position at an angle of 70° to the detector boresight, which is a good proxy for a very poor observing scenario for a single GRB scintillation detector. This is done by choosing a few random intervals in a single detector during the 31-minute period considered in the search. For each interval, a local background is fit, a detector response is generated assuming a source angle of 70° from the detector boresight, and the spectral amplitude for the same spectrum used in the targeted search is fit to the data above background. From the assumed spectrum and fitted amplitude, we estimate the corresponding flux upper limit. We find this upper limit to be $~10^{-6}$ erg s$^{-1}$ cm$^{-2}$ for a 1-s duration signal, and the variance of this upper limit shown in Figure 1 is from the range of upper limits calculated from the chosen random intervals.

https://swift.gsfc.nasa.gov/archive/grb_table/
The most important unknown parameter in the battery emission mechanism model outlined in §2.1 is the radio efficiency, $\epsilon_r$. Following equations 6 and 8 for the BNS and BHNS inspiral models respectively, we plot the derived magnetic field $B$ of the primary neutron star as a function of $\Delta t/\Omega$ in the left-panel of Figure 2. The range of possible $B$ for neutron stars in such systems is uncertain but is thought to be $\sim 10^{12} - 10^{15}$ G and is represented by the region shaded in grey. While the true radio efficiency is unknown, we use a fiducial value of $10^{-4}$ from pulsar studies (see e.g. Szary et al. 2014) and a wide range of beaming values $0.1 < \frac{\Omega}{\Omega_{10^3}} \leq 1$ (represented by the region shaded in green) for comparison. Generally though, the energetics of both FRBs fit this model for a wide range of parameter values. Fortunately, this model can be tested in another way. Mingarelli et al. (2015) describe how a precursor to the main FRB may be detectable. The radio emission associated with this model is persistent, and increasing in luminosity with separation and time in a non-linear fashion. The luminosity surges at the time of coalescence and may account for the observed FRB. However given sufficient instrument sensitivity and resolution, the emission may be detected in earlier time samples at a fraction of the main FRB’s signal-to-noise ratio (S/N) as a precursor. We can check whether a precursor to the main burst would have been detectable for FRB 180924 and FRB 190523 by calculating the battery power (equation 5) as a function of time $t(t)$ or $(t_{\text{merger}} - t)^{1/4}$, for a circular orbit.

We assume that the FRB is detected at the assumed point of closest contact ($\frac{GM}{c^2}$ for BNS and 26 km for BNS). The result is shown in the right-panel of Figure 2. FRB 180924 was detected by ASKAP at 210 per cent of the detection threshold and the time resolution of the data is 0.864 ms. The flux in the time sample that precedes the peak is about only 5 per cent lower. FRB 190523 was detected at only 115 per cent of the detection threshold, and the sampling rate is 0.131 ms. The time sample preceding the peak is about half as bright. Comparing the relative intensities in the previous bins to what is expected from the models using Figure 2, we find that FRB 180924’s precursor bin is far too bright and the next prior sample far too faint. Even in the extreme case where coalescence occurs at $2\mathcal{R}$, FRB 180924 still could not have been generated through this mechanism. As for FRB 190523, its light curve similarly rises far too rapidly. If we instead assume a spinning black hole for the BNS case (where coalescence occurs at $\frac{GM}{c^2}$), the predicted rise in power is then too drastic. More generally, though, the shapes of the light curves do not match. Therefore we can exclude the battery model for both FRBs. The only caveat here is that we have assumed that the radio emission efficiency is constant over this few millisecond timescale.

4.2 GRB jet model

The gamma-ray fluence, $\Phi_\gamma$, expected to accompany the FRB emission in this model scales with the three most uncertain quantities as $\epsilon_B P_{\gamma}^{-2} B$. The expected gamma-ray fluence as a function of the fraction of wind energy contained in the magnetic field at the shock front ($\epsilon_B$) according to equations 10 and 11 is shown in Figure 3. The resulting $\Phi_\gamma$ values are shown for a range of reasonable values of magnetic field

We comment on the results of this SGRB search throughout the following section.

4 RESULTS AND DISCUSSION

In this section, we use the measured properties of FRB 180924 and FRB 190523, as well as the upper limits on an SGRB counterpart from the previous section, to place constraints on the models described in §2. In particular, we make use of the FRB properties listed in Table 1 for convenience.
$10^{14} \text{G} \leq B \leq 10^{16} \text{G}$ and initial spin $0.001 \text{s} \leq P_0 \leq 0.01 \text{s}$ (e.g. Rowlinson et al. 2013). The worst-case sensitivity of the Fermi GBM for a 1-second burst is approximately $10^{-6} \text{ erg cm}^{-2}$ (see §3). Therefore, for $\epsilon_B < 10^{-4}$, a SGRB should have been detectable. Unfortunately the position of FRB 180924 was earth occulted when the FRB was emitted. However, Guidorzi et al. (2020) obtained upper limits in the 40–600 keV band using Insight-Hard X-ray Modulation Telescope (HXMT) data for various time integrations, including a 4.5σ upper limit of $4 \times 10^{-7} \text{ erg cm}^{-2}$ for a 1-second duration GRB. FRB 190523 was in the field of view of the Fermi GBM and there is an upper limit of $4 \times 10^{-7} \text{ erg cm}^{-2}$ for a 1-second duration GRB at the FRB’s time and position (see §3 and Figure 1). These limits rule out the SGRB jet model with $\epsilon_B < 4 \times 10^{-5}$ and $\epsilon_B < 3 \times 10^{-4}$ for FRB 180924 and FRB 190523, respectively. We note that these results are particularly dependent on the spectral index of the radio emission, which we have assumed here to be $-1.6$. A much shallower spectrum could result in a lower GRB fluence that falls below the detection threshold of current GRB instruments. Additional joint gamma-ray and FRB datasets will be required to investigate this model further.

4.3 Neutron star remnant

4.3.1 Rotational energy

Following equations 12 and 13 in §2.3.1, magnetic field strength of the supposed neutron star merger remnant as a function of pulsar spin period is represented in Figure 4. Thick shaded bands are used to show results for ranges of $10^{-6} \leq \epsilon_r \leq 10^{-1}$ and $0.01 \leq \frac{B}{\epsilon_r} \leq 1$, which are the dominant unknown variables. The results for $B$ are conservative because we have used the observing bandwidth to calculate intrinsic luminosity (equation 1). Lines of constant neutron star age are shown for reference. An initial spin period of 0.1 ms has been assumed in order to show a wider parameter space, however such low values are not thought to be possible as they exceed the NS spin break-up values of 0.55 ms and 0.8 ms for neutron stars with a mass of 2.2 $M_\odot$ and 1.4 $M_\odot$, respectively (Lattimer & Prakash 2004). If FRB 180924 and FRB 190523 are produced according to this model, the NS would have to be very young, no more than a few years old for the former and no more than a few months for the latter.

The time window for parameters to be the right values in order to produce the observed FRB is particularly short for FRB 190523. After a spin-down time of about only one day, the model pushes the limits of the parameter space, requiring very high efficiency and narrow beaming. Therefore, within the realm of this model, it is likely that giant pulses, observed as FRBs, would only be emitted very shortly after the neutron star remnant is born. The pulsar subsequently spins down, its magnetic field decreases and the ingredients required to boost efficiency and/or beaming are no longer present or abundant enough to produce giant pulses detectable by radio telescopes on Earth. This is con-
son & Anderson (2019) find that a typical magnetar remnant was falling below the detection threshold. For longer time-scales of viability for this model, one might expect repeat bursts. However, the energy distribution of giant pulses spans several orders of magnitude and follows a power-law, with the brightest bursts being the least common (Karuppusamy et al. 2010). Given the fairly modest signal-to-noise ratios with which FRB 180924 and FRB 190523 were detected, it is possible that fainter bursts are falling below the detection threshold.

Based on fits of the X-ray plateau of SGRBs, Rowlinson & Anderson (2019) find that a typical magnetar remnant with detectable associated X-ray emission would have $B \sim 10^{16}$ G and spin period $\sim 10$ ms at birth. The precise range of derived values is included in Figure 4. An X-ray plateau from energy injection by a newborn NS would have been detectable for the range of $B$ and $P$ values that overlap the marked region. While simultaneous X-ray data of neither FRB are available, such datasets would constrain the properties of a remnant NS. The duration of X-ray plateaus from SGRBs has been observed to be as long as 3 hours, however most are less than 10 minutes (Rowlinson et al. 2013). Considering the relatively short duration of X-ray plateaus, the target of opportunity observation latency is likely too long for instruments like Swift/XRT (minimum latency of 9 minutes and median 2 hours, Burrows 2010). Therefore, simultaneous radio and X-ray monitoring may be the only way to obtain a joint dataset. Alternatively, low-latency triggered radio observations following the detection of a GRB are also a possibility. An FRB search could then be conducted during the X-ray plateau phase that follows the detected GRB (previous such studies are Bannister et al. 2012; Obenberger et al. 2014; Kaplan et al. 2015; Anderson et al. 2018; Rowlinson et al. 2019). Other possible avenues toward obtaining multi-wavelength and/or multi-messenger coverage of FRBs include triggered radio observations following the detection of neutron star mergers via their gravitational waves (Yancey et al. 2015; Abbott et al. 2016; Kaplan et al. 2016; Callister et al. 2019).

4.3.2 Magnetic energy

We begin with the limit imposed on $B$ in the curvature radiation model from §2.3.3. According to equation 15, the magnetic field strength of the neutron star for FRB 180924 and FRB 190523 respectively is approximately at least $3 \times 10^{15}$ G and $1 \times 10^{15}$ G. For increasingly beamed emission, this limit decreases.

There are several unknown and/or poorly constrained variables involved in deriving a predicted flux and emission frequency for the unstable synchrotron maser model outlined in §2.3.2 and presented in Lyubarsky (2014) and elsewhere (e.g. Margalit & Metzger 2018, Metzger et al. 2019 & Beloborodov 2017, 2020). Many variables, though, are related to the nature of the upstream medium. For instance Beloborodov (2017) and Metzger et al. (2019) use electrons ejected from previous flares as the dominant material in which later ultra-relativistic ejections collide (as opposed to an electron-positron wind). Constraints on this model have been placed for FRB 180924 in Metzger et al. (2019). If we instead assume that the nebula is powered by the spin-down wind of the magnetar (Lyubarsky 2014), lower limits can be placed on the age of the magnetar based on the upper limits
on persistent radio emission for each FRB and using equation 13 and the spin down age. We find a minimum age of $\sim 8$ months and $\sim 1$ week for FRB 180924 and FRB 190523, respectively.

According to equation 14, the total isotropic emitted energy is proportional to unknown quantities as $E_{\text{iso}} \propto B p^{-1} r^{-1} \xi^{-1}$. Estimates for $p$ can come from measurements/upper-limits of persistent radio emission, assuming the FRB is produced in the nebula. Using the upper limits on the spin-down luminosity, $L_{\text{sd}}$, given by constraints on persistent radio emission, and using equation A2, we can obtain an upper limit on the pressure $P$ of the nebula ($p \propto L_{\text{sd}} r^{-2}$) assuming the distance, $r_y$, out to which the boundary between the nebula and wind occurs. A lower limit on $E_{\text{iso}}$ can then be placed using equation 14, making assumptions for the remaining unknown variables. Using $h = 0.01$, $B = 10^{16} \text{G}$, $n = 10^{-6} \text{cm}^{-3}$, and taking $p$ and $\xi$ to be the same value so that they cancel each other, we find:

$$E_{\text{iso}} > 5.8 \times 10^{41-45} \left( \frac{\Delta t}{1 \text{ms}} \right) \left( \frac{L_{\text{sd}}}{10^{48} \text{erg s}^{-1}} \right)^{-1} \text{erg}, r_y = 10^{17-19} \text{cm}. \quad (18)$$

This result is demonstrated in Figure 5 for both FRBs. Also shown are calculations of $E_{\text{iso}}$ for both FRBs according to

$$E_{\text{iso}} = 4\pi^{2} T^{2} \nu,$$

where $\nu$ is the measured burst fluence. The predicted spectrum of emission for this model is uncertain but thought to be complex (Gallant et al. 1992; Plotnikov & Sironi 2019). We therefore calculate a minimum and maximum value for $E_{\text{iso}}$ using $\Delta \nu$ and $\nu_{\text{obs}}$ respectively, in equation 19. Figure 5 allows us to compare $E_{\text{iso}}$ derived from the model (equation 18) to the values derived using equation 19. We use the following relationship for $r_y$ from Murase et al. (2016):

$$r_y \propto V_{\text{ej}}^{1/5} \xi^{2/5} P_{0}^{-1} M_{\odot}^{-1/5} T,$$

where $V_{\text{ej}} = 0.2c$ is the merger ejecta velocity, $M_{\odot}$ is the ejecta mass, $P_{0} = 10$ ms is the initial spin of the magnetar remnant and $T$ is the age of the magnetar.

We find that, for our assumed model parameters, FRB 180924 could only have been produced by a magnetar flare shocking a nebula filled with an electron-positron plasma if its age, $T$, is $8$ months $< T < 1$ yr; else persistent emission would have been detected. The results for FRB 190523 provide a larger range of ages, requiring $1 \text{ week} < T < 100$ yrs, however deeper radio searches for persistent emission are needed to provide more meaningful limits, as the current limit is 2 orders of magnitude weaker than that of FRB 180924. We note that free-free absorption in the expanding merger ejecta can impede FRB propagation up to approximately one month post-merger (e.g. Margalit et al. 2019). A flare with lower magnetic energy pushes the lower limit on the FRB energy down, whereas a denser nebula brings it proportionally higher. Constraints on the other variables of this model require a better theoretical understanding of magnetar flares and unstable synchrotron maser emission. We refer the reader to elaborate versions of the FRB maser emission theory treated in e.g. Beloborodov (2017, 2020); Metzger et al. (2019); Plotnikov & Sironi (2019); Margalit et al. (2020) for more in-depth discussion and analysis on the unknown variables involved in this problem.

### 4.3.3 NS collapse

Figure 6 shows the magnetic field of a remnant neutron star that collapses to produce the observed FRB as a function of energy conversion efficiency and beaming angle, according to equation 17 in §2.3.4. As in Figure 4, the range of typical B values for a neutron star remnant, based on X-ray plateau fits, is shown. The expected magnetic field of the neutron star depends on whether it is hypermassive (highly unstable) or supramassive (quasi-stable), and how long after formation the neutron star collapses. For instance, Piro et al. (2019) find $10^{12}$ G for a putative supramassive NS remnant of GW 170817. We use a fiducial energy conversion efficiency $\epsilon_{B} = 10^{-4}$ as in Figure 2 and a range of beaming angles $0.01 < \frac{\Omega}{\Omega_{S}} < 1$ to create the region shaded in green in Figure 6. Our results show that if $\epsilon_{B}$ is comparable to that for pulsars, the magnetic field of the remnant neutron star must be $\sim 10^{12-13} \text{G}$ for FRB 180924 and $\sim 10^{13-14} \text{G}$ for FRB 190523. In this scenario, an X-ray plateau associated with the remnant prior to collapse would be too faint to detect (Zhang & Meszaros 2001):

$$L = 1 \times 10^{45} \text{erg s}^{-1} \left( \frac{B}{10^{13} \text{G}} \right)^{2} \left( \frac{P_{0}}{1 \text{ms}} \right)^{-1} \left( \frac{R}{10^{6} \text{cm}} \right). \quad (21)$$

More generally, as one considers remnants with lower surface magnetic fields at the time of collapse, $\epsilon_{B}$ grows and increasingly narrower beaming is required. Ultimately, in order to provide better constraints on this model, multi-wavelength data are required. Given the non-detection of an SGRB in

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**Figure 5.** Lower limits on $E_{\text{iso}}$ of an FRB produced via the magnetar maser model outlined in §2.3.2, based on upper limits of persistent radio emission for FRB 180924/FRB 190523 are represented by the blue/black horizontal dash-dotted/dashed lines. The possible range of $E_{\text{iso}}$ according to equation 19 using $\Delta \nu$ and $\nu_{\text{obs}}$ to obtain the minimum and maximum values, respectively, for each FRB is shown by the shaded regions. The vertical yellow line marks the minimum age (8 months) of the magnetar remnant associated with FRB 180924 based on limits of persistent nebular emission.
be placed if deep observations constraining persistent radio emission are available. Fundamentally, all models used in this study depend on the magnetic energy density and the elusive method/efficiency of energy conversion (some version of $L \propto \epsilon_r B^2$). We have demonstrated the value of multi-wavelength datasets contemporaneous with FRB detections, which will ultimately be the best tool to break the degeneracy between possible models. In particular, joint GRB/X-ray and FRB observations would provide meaningful constraints for many of the models presented here. For instance, while the energetics of both FRBs in this study are consistent with the collapsing neutron star model for a wide range of parameters, the non-detection of a SGRB counterpart renders the scenario less likely.

The number of localized FRBs is expected to increase drastically in the coming years, thanks to telescopes with the ability to localize single bursts to sub-arcsecond precision like ASKAP and the European VLBI Network. While we are limited in our ability to definitively reject or confirm some models presented in this work with only two FRBs, a larger sample will help move towards identifying their physical origins(s). To this end, we have laid out the groundwork for future localized sources to be easily tested in the same way. We emphasize that all models except that in §2.1 can be adapted to NSs born out of core-collapse supernovae (CCSNe, the progenitors of LGRBs), for which the occurrence rate is much larger. The environment of CCSNe is, however, denser and it may be difficult for any radio emission to escape shortly after the collapse occurs.

Finally, each of the models described in this work would have accompanying gravitational wave emission. Depending on the distance out to which an FRB is localized, subthreshold GW searches can be conducted to provide further evidence for or against some of these models, for a given source. The next generation of gravitational wave detectors is expected to be 100 times more sensitive than the current instruments, which should suffice to confirm or reject these theories, if the origin of FRBs still remains unknown by then.

5 CONCLUSIONS

We have demonstrated how the information from localized FRBs can be utilized to test progenitor models. We have placed constraints on several emission models related to neutron star mergers and FRBs, for two recently localized sources, FRB 180924 and FRB 190523, which have environments reminiscent of the sites of neutron star mergers and SGRBs. We have ruled out the possibility of either FRB being produced during the final inspiral stages of a merging BNS or BHNS system through the interaction of the NS magnetosphere according to the unipolar-inductor model. We have performed a targeted sub-threshold search of Fermi GBM data for a SGRB contemporaneous with either FRB, with no resulting promising candidates. We have demonstrated that either FRB could have been generated by a very young (less than one year old) remnant pulsar through rotational energy extraction, and that it would not have necessarily been accompanied by additional detectable bursts. We have shown that stringent limits on the age of a flaring magnetar with an electron-positron wind can

Figure 6. Derived magnetic field of remnant neutron star that collapses to produce observed FRB as a function of energy conversion efficiency and beam solid angle, according to equation 17. The shaded horizontal grey band represents the range of $B$ expected for a newly born remnant neutron star with visible X-ray plateau. The shaded vertical green band denotes $\epsilon_r = 10^{-4}$ for $0.01 < \Omega \lesssim 1$, shown for reference, though a wide range of values is acceptable.

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DATA AVAILABILITY

The data used for the GRB search presented in this article are hosted through the Fermi Science Support Center and NASA’s High Energy Astrophysics Science Archive Research Center. The data used for FRB 180924 and FRB 190523 can be accessed at https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/daily/2018/09/24/current/ and https://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/daily/2019/05/23/current/, respectively.
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APPENDIX A: THE FLARING MAGNETAR MODEL
Here, we show a detailed derivation of equation 14, obtained following and building on the model presented in Lyubarsky (2014). The magnetar flares start in the form of magnetohydrodynamic waves (Alfvén waves) that propagate in the magnetosphere, sweeping up field lines to form a pulse that travels through the magnetar’s wind. The magnetic field, $B_p$, stored in the pulse is some fraction, $b$, of the magnetic field at the magnetar’s surface, $B$, and proportional to the magnetar’s radius, $R$, and the pulse’s distance from the magnetar surface, $r$:

$$ B_p = b B R_s r, \quad b < 1. $$  \hspace{1cm} (A1)

The magnetar wind is composed of magnetized electron positron plasma and its luminosity is determined by the spin-down luminosity $L_{sd} = \dot{E}$ defined in equation 13. The wind’s end boundary occurs when the wind’s bulk pressure

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where we have made use of the fact that Lyubarsky 2014, equation 11):
\[ p = \frac{L_{\text{iso}}}{4\pi r^2 c^2}. \]  
(A2)

There is a termination shock at the radius at which this balance occurs, and a hot wind bubble (like a nebula) consequently forms. Therefore, \( p \) is the pressure at the termination shock. The termination shock radius, \( r_s \), is found by inserting equation 13 into equation A2:
\[ r_s = \sqrt{\frac{4\pi B^2 R_0^6}{3p \rho^4 c^4}}. \]  
(A3)

When the pulse reaches the termination shock, it meets a discontinuity as the upstream medium suddenly changes from the cold wind to the hot wind/nebula. It blasts the plasma in the nebula outward, generating a forward shock that propagates through the nebula’s plasma. Equation A3 can be substituted into equation A1 to find \( B_p \) at the time of the blast:
\[ B_p = \frac{\sqrt{3} R_0 h_0^{1/2} \rho_2^2 c^2}{2 \xi^{3/2} R_0^2}. \]  
(A4)

A contact discontinuity exists between the reverse and forward shocks, and defines a boundary for the shocked plasma in the nebula (think of the contact discontinuity moving with the propagating Alfvén wave). At this contact discontinuity, the pressure (magnetic energy density, \( \frac{B_p^2}{8\pi} \)) of the pulse is equivalent to the bulk pressure of the hot plasma in the nebula crossing the forward shock. Since the pressure behind the shock is much greater than the unshocked plasma in the nebula ahead of the shock, we use the limiting density ratio which is 4 if we treat the plasma as a non-relativistic monatomic gas (adiabatic index \( \gamma = 5/3 \)) (Zel’dovich & Raizer 2002). Finally, we must consider that the contact discontinuity moves with Lorentz factor \( \Gamma \) with respect to the observer. The particles in the plasma are boosted by a factor \( \Gamma \) and the density too increases by \( \Gamma \). The resulting pressure balance is then:
\[ \frac{B_p^2}{8\pi} = 4\xi p \Gamma^2, \quad \xi < 1, \]  
(A5)

where dimensionless \( \xi \) takes into account that some quantity of the high energy particles in the shocked plasma will lose their energy before they are able to enter the nebula, thereby decreasing the pressure. We solve for \( \Gamma \) combining equations A4 and A5:
\[ \Gamma = \left( \frac{3}{128} \right)^{1/4} \frac{b^{1/2} \sqrt{c} P}{\pi R^2 \xi^{1/2}}. \]  
(A6)

The magnetic field of the wind runs perpendicular to \( B_p \) and the shock is mediated by that field. The gyration of the shocked particles creates an unstable synchrotron maser, that produces low-frequency emission, a fraction of which (\( \eta \)) manages to escape thermalization through the upstream unshocked plasma. For a pulse that travels a distance \( \Delta r \) in the nebula, the isotropic energy of the escaped emission is (Lyubarsky 2014, equation 11):
\[ E_{\text{iso}} = \eta 4\pi r_s^2 n m_e c^2 \Gamma^2 \Delta r, \]  
(A7)

where we have made use of the fact that \( 4\pi r_s^2 c n \) is the number of particles entering the shock per unit time and \( n \) is the nebula’s particle density. Finally, we use Doppler compression to find a relationship between observed burst duration \( \Delta t \) and \( \Delta r \) (\( \Delta t = \frac{\Delta r}{c \eta} \)) and substitute \( \Delta t \) into equation A7, and, after full expansion, obtain:
\[ E_{\text{iso}} = \frac{\eta B^2 R^2 n m_e c^3 \sqrt{2} \Delta t}{16 c^3}. \]  
(A8)

We now address emission frequency. The particles gyrate at the Larmor frequency
\[ \nu_p = \frac{e B_p}{2\pi m_e c \Gamma} = \left( \frac{3}{2} \right) \frac{1/4 b^{1/2} \sqrt{c} \xi^{1/4} e P^{1/2} \sqrt{p}}{m_e \pi R^{3/2} \Gamma}, \]  
(A9)

where \( m_e \) is the electron rest mass and \( e \) is the electron charge. The radio emission is dominated by maser emission at this frequency (Lyubarsky 2014). The value of \( \nu_p \) ranges from tens to hundreds of megahertz depending mostly on the pressure of the nebula \( p \) (\( P \) for a magnetar is likely to be approximately one second). However, for magnetically dominated plasmas, particle-in-cell simulations reveal complex shock structure that actually increases the peak frequency by several factors (for high magnitization, \( \sigma > 1 \)) (Plotnikov & Sironi 2019). Furthermore, the spectrum of emission extends to higher frequencies (Gallant et al. 1992; Plotnikov & Sironi 2019). In this way, GHz frequencies can be attained.

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