Implications of a “Fast Radio Burst” from a Galactic Magnetar

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ABSTRACT

A luminous radio burst was recently detected in temporal coincidence with a hard X-ray flare from the Galactic magnetar SGR 1935+2154 with a time and frequency structure consistent with cosmological fast radio bursts (FRB) and a fluence within a factor of ≲10 of the least energetic extragalactic FRB previously detected. Although active magnetars are commonly invoked FRB sources, several distinct mechanisms have been proposed for generating the radio emission which make different predictions for the accompanying higher frequency radiation. We show that the properties of the coincident radio and X-ray flares from SGR 1935+2154, including their approximate simultaneity and relative fluence $E_{\text{radio}}/E_X \sim 10^{-5}$, as well as the duration and spectrum of the X-ray emission, are consistent with extant predictions for the synchrotron maser shock model. Rather than arising from the inner magnetosphere, the X-rays are generated by (incoherent) synchrotron radiation from thermal electrons heated at the same internal shocks which produce the coherent maser emission as ultra-relativistic flare ejecta collides with a slower particle outflow (e.g. as generated by earlier flaring activity) on a radial scale $\sim 10^{11}$ cm. Although the rate of SGR 1935+2154-like bursts in the local universe is not sufficient to contribute appreciably to the extragalactic FRB rate, the inclusion of an additional population of more active magnetars with stronger magnetic fields than the Galactic population can explain both the FRB rate as well as the repeating fraction, however only if the population of active magnetars are born at a rate that is at least two-orders of magnitude lower than that of SGR 1935+2154-like magnetars. This may imply that the more active magnetar sources are not younger magnetars formed in a similar way to the Milky Way population (e.g. via ordinary supernovae), but instead through more exotic channels such as superluminous supernovae, accretion-induced collapse or neutron star mergers.

Keywords: Radio transient sources (2008) — Magnetars (992) — Soft gamma-ray repeaters (1471)

1. INTRODUCTION

Fast radio bursts (FRBs) are bright, millisecond duration pulses of coherent radio emission with dispersion measures (DM) well in excess of Galactic values (Lorimer et al. 2007; Thornton et al. 2013; see Petroff et al. 2019, Cordes & Chatterjee 2019 for reviews), and hence pointing to an extragalactic origin. The precise mechanisms powering FRBs remain a topic of debate, in large part due to the small number of well-localized events, as well as the fact that some FRBs appear to repeat (Spitler et al. 2016; Chatterjee et al. 2017; CHIME/FRB Collaboration et al. 2019) while others do not.

Many theoretical models have been proposed for FRBs (see Platts et al. 2019 for a catalog). Perhaps the most well-studied models are those which postulate that FRBs arise from the flaring activity of strongly-magnetized neutron stars (NS) known as “magnetars” (Popov & Postnov 2013; Lyubarsky 2014; Kulkarni et al. 2014; Katz 2016; Metzger et al. 2017; Beloborodov 2017; Kumar et al. 2017). Evidence in favor of magnetars as FRB sources include: (1) high linear polarization and large rotation measures (e.g. Masui et al. 2015; Michilli et al. 2018), indicative of a strongly-magnetized cen-
tral engine and environment; (2) spatial association with star-forming regions, in the two repeating events where VLBI imaging enables precise sky localizations (Bassa et al. 2017; Tendulkar et al. 2017; Marcote et al. 2020); (3) statistical properties of the bursts’ repetition consistent with those of Galactic magnetar flares (e.g. Wadiasingh & Timokhin 2019; Cheng et al. 2020); (4) a sufficiently high volumetric rate of magnetar birth to plausibly explain the observed FRB rate (e.g. Nicholl et al. 2017), unlike other models involving rare cataclysmic events (Ravi 2019).

Despite these hints, several properties of the growing sample of FRBs appear—at least at first glance—to be in tension with magnetars as a primary source. The first repeating source, FRB 121102 (Spitler et al. 2016), has been bursting nearly continuously (albeit interrupted by extended “dark” periods) for over 7 years; no known magnetar in our Galaxy matches this continuous level of activity. One is forced to the conclusion that at least the most active repeating FRB sources arise from magnetars which are somehow different from the Galactic population, e.g. being of very young age (Metzger et al. 2017; Beloborodov 2017), formed via alternative channels than ordinary core-collapse supernovae (CCSNe; Metzger et al. 2017; Margalit et al. 2019; Zhong & Dai 2020), or possessing other atypical property such as an unusually long rotational period (Wadiasingh & Timokhin 2019).

The recurrent fast radio burst FRB 180916 was recently shown by the CHIME/FRB collaboration to exhibit a 16 day period of unknown origin (The CHIME/FRB Collaboration et al. 2020). Again, although known Galactic magnetars offer no clear explanation for periodic behavior at this scale (with the possible exception of candidate magnetar 1E 1613485055 which has a measured period of 6.7 hr; De Luca et al. 2006), reasonable variations in the properties of extragalactic magnetars (e.g. extremely slow rotation, precession, or presence in a binary) offer a potential explanation for the periodic behavior at this scale. The double-peaked burst, detected independently by CHIME (Bandura et al. 2014) and STARE2 (Bochenek et al. 2020b), was temporally coincident with an X-ray burst of significantly larger fluence (Mereghetti et al. 2020a; Zhang et al. 2020a; Mereghetti et al. 2020b). This “fast radio burst” is still a factor of ∼ 10 less energetic than the weakest FRB previously detected from any localized cosmological FRB source. It nevertheless represents an enormous stride in bridging the energy gap between Galactic magnetars and their hypothesized extragalactic brethren, providing new support to magnetar FRB models.

Here, we explore several implications of this discovery for the broader magnetar-FRB connection. We emphasize that there exists no single “magnetar model”, but rather a range of models which make drastically different predictions for the mechanism and location of the radio emission and the accompanying higher frequency radiation, some of which this discovery lend credence to and others for which the model is placed in tension.

This paper is organized as follows. In §2 we summarize the observational picture regarding SGR 1935+2154 and its recent radio/X-ray activity. In §3 we address several broad implications of this discovery in the context of magnetar models for cosmological FRBs. In §4 we discuss the implications of the coincident radio and X-ray flare from SGR 1935+2154 for extant variations of the magnetar model. Finally, we summarize and provide bulleted conclusions in §5.

2. SUMMARY OF OBSERVATIONS

2.1. SGR 1935+2154

SGR 1935+2154 is a Galactic Soft Gamma Repeater (SGR) first discovered by Neil Gehrels Swift Observatory’s Burst Alert Telescope (BAT) as a GRB candidate through a series of soft bursts from the Galactic plane (Stamatikos et al. 2014; Lien et al. 2014).
The source is associated with supernova remnant (SNR) G57.2+0.8 (Gaensler 2014). Distance estimates are uncertain, ranging from 6.6-12.5 kpc (Sun et al. 2011; Pavlović et al. 2013; Kothes et al. 2018; Zhou et al. 2020; Mereghetti et al. 2020b), and throughout this paper we adopt a distance of $d = d_{10} \cdot 10$ kpc. Subsequent discovery of coherent X-ray pulsations of SGR 1935+2154 with the Chandra X-ray Observatory established the spin period of the magnetar, $P \simeq 3.2$ s (Israel et al. 2014, 2016). XMM-Newton and NuSTAR observations of the source during outburst in 2015 provided the magnetar’s spin-down rate, $\dot{P} \simeq 1.43 \times 10^{-11}$ s$^{-1}$, which implies a surface dipolar magnetic field $B \simeq 2.2 \times 10^{14}$ G, a spin-down luminosity $L_{\text{sd}} \simeq 1.7 \times 10^{34}$ erg s$^{-1}$, and characteristic spin-down age of $P/2\dot{P} \simeq 3600$ years.

We note, however, that the age estimate based on the SNR association, $\gtrsim 16$ kyr, is significantly older (Zhou et al. 2020; see also Kothes et al. 2018). This discrepancy between the dipolar and the SNR age estimates is similar to the one observed in the other magnetar associated with a SNR, Swift J1834.9–0846 (Granot et al. 2017; with a spin-down age of 4.9 kyr and a SNR age between 5 and 100 kyr). Since the dipolar age estimate is expected to be inaccurate in case either the surface magnetic field evolves with time (e.g. Colpi et al. 2000; Dall’Osso et al. 2012; Beniamini et al. 2019) or else the spin evolution is to be inaccurate in case either the surface magnetic field evolves with time (e.g. Colpi et al. 2000; Dall’Osso et al. 2012; Beniamini et al. 2019) or else the spin evolution is not dominated by dipolar radiation (Thompson & Blaes 1998; Harding et al. 1999; Beniamini et al. 2020). An "FRB" from SGR 1935+2154

On April 10, 2020, a short soft X-ray burst was triangulated by the IPN to SGR 1935+2154 (Svinkin et al. 2020). This was followed by a slew of bursts, extending to hard X-rays, detected over the following couple of weeks (Veres et al. 2020; Ridnaia et al. 2020a; Cherry et al. 2020; Hurley et al. 2020; Ridnaia et al. 2020b; Palmer 2020; Ricciarini et al. 2020; Marathe et al. 2020; Ridnaia et al. 2020c; Mereghetti et al. 2020a; Ridnaia et al. 2020d; Lipunov et al. 2020; Younes et al. 2020; Kennea et al. 2020).

On April 28, as part of this period of enhanced source activity, a bright millisecond radio burst, the first of its kind, was detected from SGR 1935+2154 (Scholz & CHIME/FRB Collaboration 2020). The radio burst was associated with a short hard X-ray burst (Mereghetti et al. 2020a) peaking at energies $E_{\text{peak}} \sim 70$ keV (Zhang et al. 2020a; see also Mereghetti et al. 2020b). The detection by the CHIME/FRB backend in the 400–800 MHz band comprise two sub-burst components. The bursts, each $\sim 5$ ms wide and separated by $\sim 30$ ms had a reported DM of 332.81 pc cm$^{-3}$. This DM value is consistent with the observed $\approx 8.6$ s delay of the radio burst (at 400 MHz) with respect to the peak of the X-ray counterpart flare as being almost entirely due to the cold plasma time delay (Mereghetti et al. 2020a; Zhang et al. 2020b; Mereghetti et al. 2020b). An independent detection of the burst was also reported from the STARE2 radio feeds at the 1.4 GHz band (Bochenek et al. 2020a). They report the burst arrival time and the DM value to be consistent with the CHIME detection, and constrain the peak fluence to be $> 1.5 \text{ MJy ms}$. The much lower flux detected by CHIME versus STARE2 may be at least partly attributable to the fact that the burst was detected in the sidelobes of CHIME.
The compelling nature of this burst led to a search for track-like muon neutrino events with the IceCube observatory, with no significant neutrino signals detected along its direction (Vandenbroucke 2020). Likewise, VLA followup of the source found no persistent or afterglow radio emission down to a flux of ∼ 50 µJy (Ravi et al. 2020a,b).

The millisecond-duration high-brightness temperature radio burst of SGR 1935+2154 is unlike any other pulsar/magnetar phenomenology observed to date, with a luminosity exceeding that of even the most luminous Crab giant pulses (e.g. Mickaliger et al. 2012) by several orders of magnitude. Instead, the burst properties are suggestively similar to cosmological FRBs. As pointed out by Bochenek et al. (2020a), placed at the distance of the nearest localized FRB 180916, ∼ 149 Mpc (Marcote et al. 2020), the SGR 1935+2154 outburst would have been potentially detectable as a > 7 mJy ms burst, coming close to, albeit still lower than typical FRB fluences. Stated energetically, SGR 1935’s emitted radio energy is $E_{\text{radio}} > 4 \times 10^{34} d_{10}^2 \text{erg}$, within a factor of 10 of the lowest-energy burst observed from any cosmological FRB of known distance to date, ∼ 5 × 10^{35} erg (Marcote et al. 2020). This is illustrated in Fig. 1. Also, at least from the standpoint of its X-ray fluence and duration, the “FRB”-generating flare from SGR 1935+2154 appears to be fairly typical among Galactic magnetar flares (Fig. 2; however, see discussion in §3). The immediate implication of all this is that magnetar activity akin to the burst observed from SGR 1935+2154 should be contributing to the extragalactic FRB population.

3. SGR 1935 IN THE CONTEXT OF COSMOLOGICAL FRBS

In this section, we assume that all FRBs are produced by magnetar flares, with universal properties motivated by the SGR 1935 burst. Proceeding under this strong assumption, we explore the implications for FRB energetics and repetition rates. We are led to conclude that “ordinary” magnetars with activity-levels similar to SGR 1935 cannot alone explain the observed FRB population.

As discussed in §2, a contemporaneous X-ray flare was detected in coincidence with the radio burst of SGR 1935. The timing coincidence and similar substructure in both radio and X-ray bands implicates that the two be interpreted as counterparts (Mereghetti et al. 2020a; Zhang et al. 2020b; Mereghetti et al. 2020b). The ratio between the radiated energy of the radio burst and its X-ray counterpart is

$$\eta \equiv \frac{E_{\text{radio}}}{E_X} \sim 10^{-5}. \quad (1)$$

Here we have calculated the X-ray burst energy $E_X \approx 8 \times 10^{39} d_{10} \text{erg}$ using the fluence 6.8 × 10^{-7} erg cm^{-2} reported by the Hard X-ray Modulation Telescope (HXMT; Zhang et al. 2020a). A similar fluence was reported by INTEGRAL (Mereghetti et al. 2020b). Likewise, we have estimated the radio energy $E_{\text{radio}} \approx 4 \times 10^{34} d_{10} \text{erg}$ by adopting the 1.5 MJy ms lower limit on the fluence reported by STARE2 (Bochenek et al. 2020a) and assuming a frequency width corresponding to the instrument bandwidth $BW \approx 250 \text{MHz}$ (Bochenek et al. 2020b). The true value of $E_{\text{radio}}$ (and hence $\eta$) may be somewhat larger than this estimate because the STARE2 radio fluence is quoted as a lower limit. Furthermore, the fact that the same burst was detected also by CHIME at lower radio frequencies (albeit at a lower reported fluence, possibly attributable to the detection occurring in an instrumental sidelobe) suggests its spectral energy distribution is broadband, such that the true burst energy could be larger by a factor of $\gtrsim \nu / BW \approx 6$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Repetition rate above a given emitted radio energy as a function of energy for SGR 1935+2154 and localized FRBs: the repeating sources FRB 121102 (Law et al. 2017; Gourdji et al. 2019) and 180916 (Marcote et al. 2020; The CHIME/FRB Collaboration et al. 2020), and apparently non-repeating FRBs 180924 (Bannister et al. 2019), 190523 (Ravi et al. 2019), and 181112 (Prochaska et al. 2019). The energy of the recent radio burst from SGR 1935+2154 is a factor of ∼ 10 d_{10} lower than the least energetic extragalactic FRB of known distance. Applying the same ratio of radio to X-ray fluence measured for SGR 1935+2154 $\eta \sim 10^{-5}$ (eq. 1) to giant magnetar flares would imply that Galactic magnetars are capable of powering even the most energetic cosmological FRBs. However, a stark discrepancy exists between the activity (burst repetition rate) of Galactic magnetars and the sources of the recurring extragalactic FRBs (§3). Scaling from the magnetic field and age of SGR 1935+2154 implies that magnetar progenitors of extragalactic FRBs must have larger $B$-fields and younger age (see §3.1 for further details).}
\end{figure}
The low value of $\eta$ illustrates that magnetars are inefficient FRB producers. Implications of this fact for specific magnetar FRB models are discussed later (§4). Regardless of the emission mechanism, the active lifetime of cosmological recurrent FRB sources cannot be long if FRB emission is similarly inefficient for such sources. For the activity rate and radio fluences of FRB 121102 (e.g. Law et al. 2017), the radio-inefficiency $\eta \sim 10^{-5}$ implies that the FRB-generating engine must be losing energy at a rate of $\sim$several $\times 10^{39}$ erg s$^{-1}$ (itself only a lower-limit if the luminosity-function is energetically-dominated by low energy undetectable bursts; Gouldji et al. 2019). For FRB 180916 the repetition rate and luminosity function point to qualitatively similar requirements on the power output of the central engine, $\gtrsim 5 \times 10^{39}$ erg s$^{-1}$ (The CHIME/FRB Collaboration et al. 2020).

If recurrent FRBs are powered by magnetars, then their active lifetime is at the very least limited by their total magnetic energy reservoir $E_{\text{mag}} \sim 3 \times 10^{49}$ erg $(B/10^{16})^2$,

$$\tau_{\text{active}} \sim \frac{E_{\text{mag}}}{\dot{E}_{\text{FRB}}/\eta} \sim 200 \text{ yr} \left(\frac{B}{10^{16} \text{ G}}\right)^2 \left(\frac{\eta}{10^{-5}}\right),$$

where $B$ is the interior magnetic field strength and we have taken $\dot{E}_{\text{FRB}} \sim 5 \times 10^{34}$ erg s$^{-1}$ motivated by FRB 121102 (Law et al. 2017). Even for large interior fields $B \gtrsim 10^{16}$ G, the maximum active lifetime is significantly shorter than the 16 kyr estimated age of SGR 1935+2154 (Zhou et al. 2020), or indeed of any other known Galactic magnetar.

Based purely on their X-ray behavior, magnetars as active as FRB 121102 or other repeating FRB sources do not exist in our own Galaxy. These points suggest that if cosmological FRBs originate from magnetar progenitors, at least a subset of these magnetars must be far more active than SGR 1935+2154, and are perhaps formed via different mechanisms than Galactic magnetars (Margalit et al. 2019). We further quantify this point in the next section by calculating the extragalactic detection rate of SGR 1935+2154-like events.

Before turning to extragalactic sources, we examine more closely the burst from SGR 1935+2154 in light of other bursts from Galactic magnetars observed in the past $\sim 20$ years. Figure 2 depicts the X-ray fluence ($F_X$) and the duration ($t_X$) of the recent X-ray bursts from SGR 1935+2154, alongside other bright bursts$^1$. Here, the duration of the burst ($t_X$) is defined as the interval of time when 5% and 95% of the total background subtracted counts are recorded (Göğüş et al. 2001). A rough correlation is seen between the fluence and duration (Göğüş et al. 2001), approximately satisfying $F_X \propto t_X^{1.54}$ consistent with reports in the magnetar literature for the bursts from single sources (Gavriil et al. 2004). Although the bursts from SGR 1935+2154 are bright, they fit within this trend, and are not exceptional in terms of their fluence or overall-envelope duration with respect to bright bursts from other Galactic magnetars. However, the burst associated with SGR 1935+2154’s radio emission may have exhibited a harder spectrum than other bursts (Mereghetti et al. 2020b), indicating that perhaps this particular burst was produced via a different emission mechanism, and that this mechanism may be related to FRB production. In §4.2.2 we present a scenario in which shock-powered X-rays are generated concurrently with the coherent radio emission; however, as thermal X-rays may be produced in the magnetosphere during flaring by other mechanisms, it is plausible that

$^1$ The duration and fluence are obtained from an extensive search of NASA GCN circulars archive (https://gcn.gsfc.nasa.gov/gcn3_archive.html), and The Astronomers’ Telegram (http://astronomerstelegram.org/).
multiple sources of X-ray emission contribute to different flares, or within a single burst. Nonetheless, this raises the question of whether other FRBs from Galactic magnetars should have already been observed in the past?

Assuming the value of $\eta$ from the recent radio detection of SGR 1935+2154 is universal across all flares, we predict the fluence of the radio emission ($F_{\text{radio}}$) that should accompany the X-ray bursts from a large population of Galactic magnetar outbursts over the past $\sim 2$ decades (the same sample shown in Fig. 2). Figure 3(a) shows $F_{\text{radio}}$ as a function of the burst date, with reference to the estimated sensitivity (hatched regions) of STARE2 and CHIME/FRB telescopes. We see that two flares preceded the April 28th FRB event from SGR 1935+2154 with higher predicted $F_{\text{radio}}$—one on April 10th 2020 (Veres et al. 2020) and another on April 22nd 2020 (Ridnaia et al. 2020b). These events fall within the nominal STARE2 observable window, despite no reported radio detection. We note that relatively few magnetar flares have occurred over the last few years, when STARE2 and CHIME have been operational, at a fluence that would have been detectable by these instruments. Also note that the on-beam CHIME/FRB sensitivity shown is not the relevant one for most bursts, which will occur in the sidelobes of the telescope.

In the exceptional case of the giant flare from SGR 1806–20 (Palmer et al. 2005; Hurley et al. 2005), the upper limit on radio emission (Tendulkar et al. 2016; estimated based on sidelobe sensitivity of Parkes) is smaller than the predicted radio fluence (for $\eta \sim 10^{-5}$) by a factor of $\sim 100$ (Fig. 3; red triangle and square, respectively). As we discuss later in § 4.2.2, this may be understood in some magnetar FRB models, for different beaming properties of the radio emission relative to the higher frequency counterpart in giant flares as opposed to less energetic magnetar flares. More generally, the fact that one FRB was observed out of only a few magnetar bursts where we might have expected a detection, suggests that the FRB beaming is rather modest. The beaming can be directly probed in the future, once more X-ray bursts from SGR 1935+2154 with comparable luminosities are observed, by searching for a possible correlation between FRB detectability and the rotational phase of the magnetar.

Using the X-ray burst fluence for each source, and distance estimates from the McGill magnetar catalogue (Olausen & Kaspi 2014)\(^2\), we estimate the intrinsic burst X-ray luminosity ($L_X$). For the selected bursts, we depict in Figure 3 the value of $L_X$ normalized to the individual source’s “magnetic Eddington luminosity” $L_{\text{min}}$ (Paczynski 1992; see also §3), a rough scale for the minimum luminosity burst that is capable of driving baryonic outflows via radiation pressure.

\(^2\) http://www.physics.mcgill.ca/~pulsar/magnetar/main.html
quantity of mass in the external medium needed in the synchrotron maser scenario is extremely modest.

3.1. Rates: A Single Magnetar Population?

Given the 3.6 steradian field-of-view of STARE2 (Bochenek et al. 2020b) and the fact that a single magnetar radio burst has been detected during the ~300 day operating period of the experiment, we estimate the rate of SGR 1935+2154-like magnetar radio bursts (taking the number of active magnetars in the Galaxy to be \( N = 29 \); Olansen & Kaspi 2014) to be \( \lambda_{\text{mag}} \in [0.36, 80] \times 10^{-2} \) per magnetar per year at 95% confidence (assuming Poisson statistics; Gehrels 1986).

The radio-burst activity (repetition) rate of SGR 1935 estimated above is plotted in Fig. 1 in comparison to cosmological FRBs. We show here the full sample of published localized FRB sources, where the radio-emitted (isotropically-equivalent) energy can be reliably calculated: repeating FRB 121102 (yellow; Law et al. 2017; Gourdji et al. 2019), the recently localized CHIME repeater FRB 180916 (purple; Marcote et al. 2020; The CHIME/FRB Collaboration et al. 2020), and the apparently non-repeating FRBs 180924 (green, upper limits denoted by upside-down triangles; Bannister et al. 2019), 190523 (brown; Ravi et al. 2019), and 181112 (blue; Prochaska et al. 2019). We have used quoted rates where possible (Law et al. 2017; Gourdji et al. 2019; The CHIME/FRB Collaboration et al. 2020) and otherwise estimated Poissonian rates based on quoted field exposure times, where available. Grey markers with errorbars show the repetition rate (from Tendulkar et al. 2016) and radio energy implied if some giant magnetar flares produce radio emission with the same efficiency \( \eta \sim 10^{-5} \) between X-ray and radio fluences. This indicates that Galactic magnetars may be energetically capable of powering even the most luminous FRBs, though for one particular flare from SGR 1806-20 such radio emission is ruled out (Tendulkar et al. 2016). Finally, we note that radio pulses observed from M87 by Linscott & Erkes (1980) ~40yr ago, though unconfirmed by subsequent followup, may have been the earliest recorded FRB detections, and correspond to \( E_{\text{radio}} \sim 10^{38} \) erg on this figure.

Figure 1 shows that, at comparable energy, the SGR 1935 radio burst is ~10^{-5} less frequent than FRB 180916 bursts. Within the hypothesis that magnetars are also the progenitors of such cosmological FRB, this stark discrepancy in activity rate may be attributable to the magnetar age and internal field strength. Indeed, Margalit et al. (2019) show that magnetar activity scales strongly with magnetic field, \( \dot{E} \propto B^{3.2} \) (Dall’Ossio et al. 2012; Beloborodov & Li 2016). This is shown schematically with the dotted-blue contours in Fig. 1, assuming that \( \lambda(> E)E \sim \dot{E} \propto B^{4.2} \), and scaling the \( B \)-field from ~2 \times 10^{14} G, the external dipole field of SGR 1935+2154 (note that the internal field is what sets \( \dot{E} \), and thus we implicitly assume that the internal field is comparable to the external dipole field for this object). This assumed \( B \)-field implies an active lifetime of ~70 kyr for SGR 1935 (e.g. Margalit et al. 2019, their eq. 1), consistent with the \( \gtrsim 16 \) kyr source age. Contours of active lifetime (~magnetar age) are also shown in Fig. 1 (grey shaded regions), scaling from SGR 1935’s estimated age as \( \tau_{\text{active}} \propto B^{-1.2} \) (Dall’Ossio et al. 2012). The 5 order of magnitude higher repetition rate of FRB 180916 would thus imply \( B_{\text{180916}} \sim (10^5)^{1/3} B_{\text{SGR1935}} \sim 10^{16} \) G, in agreement with separate lines of argument, e.g. requirements for FRB 180916 periodicity to be attributable to magnetar precession (Levin et al. 2020).

An alternative possibility is that the repetition rate increases significantly with the periodicity (Wadiasingh et al. 2020). In this case, the periodicity of 180916 (and its high activity relative to SGR 1935+2154) may be ascribed to an extremely long period magnetar (Beniamini et al. 2019) of of the CCSN rate, \( \Gamma_{\text{CCSN}} \approx 0.9 \) (Beniamini et al. 2019) of the CCSN rate, \( \Gamma_{\text{CCSN}} \approx (0.71 \pm 0.15) \times 10^{-3} \) yr^{-1} (Li et al. 2011). Thus, the rate of potentially-detectable FRBs produced by SGR 1935+2154-like bursts is

\[
R(> F_{\text{lim}}) \approx \frac{4}{3} D_{\lim}^3 f_{\text{CCSN}} \Gamma_{\text{CCSN}} \tau_{\text{active}} \lambda_{\text{mag}} \approx 0.004 \text{ yr}^{-1} \text{ Jy}^{-1} \text{ s}^{-1}
\]

This is much lower than the Parkes estimated FRB rate \( \approx 1.7 \pm 0.9 \times 10^{4} \) skew^{-1} day^{-1} above a fluence of 2 Jy ms (Bhandari et al. 2018).

\[3^3\]Also note that activity may increase with the NS mass, because at sufficiently high central densities the star can cool through direct URCA reactions, which hastens the release of magnetic energy from the core (Beloborodov & Li 2016).
The estimate above shows that magnetars bursting at the same rate and energy as the April 28th SGR 1935+2154 radio burst cannot contribute noticeably to the FRB population. However, clearly magnetar flares span a range of energies (Fig. 2), making it natural to ask whether SGR 1935+2154-like magnetars can reproduce the FRB rate if one extrapolates radio production with a similar efficiency to more energetic magnetar flares.

We therefore calculate the all-sky rate of FRBs above a limiting fluence threshold assuming that all magnetars follow a luminosity-distribution \( \lambda_{\text{mag}}(>E) \propto (E/E_{\text{min}})^{-\gamma} \) for burst energies between \( E_{\text{min}} \) and \( E_{\text{max}} \). We set \( E_{\text{max}} = \eta E_{\text{mag}} \propto B^2 \) dictated by the magnetic energy reservoir of the magnetar (this is consistent with the energies of the three observed Galactic giant flares relative to the magnetic dipole energies of the magnetars producing them, see e.g. Tanaka et al. 2007), and fix the minimum energy to that observed for the April 28th SGR 1935+2154 flare\(^4\). The magnetar birth-rate \( \Gamma_{\text{birth}}(z) \) is assumed to follow the cosmic star-formation rate (Hopkins & Beacom 2006) and is anchored to 10\(^\%\) the CCSN rate at \( z = 0 \) (Li et al. 2011). The integrated rate is thus

\[
\mathcal{R}(>E_{\text{lim}}) = \int dV(z) \Gamma_{\text{birth}}(z) \tau_{\text{active}} \\
\times \int dE \lambda_{\text{mag}}(E) \Theta \{E - 4\pi D_L(z)^2 F_{\text{lim}}\}.
\]

We set \( \tau_{\text{active}} = 24 \text{ kyr} \) and fix \( \lambda(>E_{\text{min}}) \) to the estimated rate of SGR 1935 radio bursts. The former is determined from the minimum SNR age estimated by Zhou et al. (2020) and scaled to our adopted distance of 10 kpc. We then integrate over cosmological redshift and calculate the rate as a function of the slope of the luminosity-function, \( \gamma \). Fig. 4 shows the resulting all-sky rate as a function of \( \gamma \) (the only free variable in the calculation). For large \( \gamma \), the rate is dominated by bursts of energy \( \sim E_{\text{min}} \) and we recover the result of eq. (3), namely that the rate of Galactic magnetars is too low compared to cosmological FRBs. However, for \( \gamma < 1.5 \) the rate becomes dominated by the high-energy tail of the luminosity function, and the number of detectable magnetar radio bursts increases. In particular, we find that, for \( \gamma \lesssim 1 \)—magnetars of a similar kind to SGR 1935+2154 can account for the entire FRB rate.

Although extending the luminosity function of radio bursts to higher energies can allow (for certain values of \( \gamma \)) “ordinary” magnetars similar to SGR 1935+2154 to reproduce the number of observed FRBs, this scenario falls short of explaining many other observables. In particular, and as discussed previously—the per-source activity rate for such a population would be far too low to explain prolific repeaters like FRBs 121102 and 180926. For the same reason, most FRB sources would be detected only once and the relative number of repeaters versus apparently-non-repeaters would be very small. The scenario would also predict average FRB source distances that are far nearer than localized sources or DM-estimated distances.

3.2. Two-Component Population

To further explore the possibilities on possible magnetar progenitors of cosmological FRBs, we extend the calculation of the previous section and model a two-component magnetar population as necessitated by the observations: magnetars with low activity levels like SGR 1935+2154, and magnetars that are very active. A natural question this will allow us to address is whether...
the active population is consistent with an earlier evolutionary stage (a younger version) of the same SGR 1935+2154-like population, or whether one requires a distinct population altogether (e.g. a rare subset of magnetars born through unique channels).

We again calculate the all-sky FRB rate using eq. (4), accounting for the two populations contributing to FRB production. As before, the only free parameter describing the “ordinary magnetar” population is the luminosity-function slope $\gamma$. The second, “active”, population is then scaled from the former population as a function of the internal magnetic field $B$ and relative birth-rate $f_{\text{CCSN}}$.

The magnetic field of the magnetar enters in setting $E_{\text{max}} \propto B^2$, the active lifetime of sources $\tau_{\text{active}} \propto B^{-1.2}$ (Dall’Osso et al. 2012; Beloborodov & Li 2016), and the repetition-rate $\lambda_{\text{mag}} (> E_{\text{min}})$. The latter is proportional to $\propto B^{3.2}$ for $\gamma > 1$ and $\propto B^{1.2+2\gamma}$ for $\gamma < 1$.

We normalized $\tau_{\text{active}}$ and $\lambda_{\text{mag}}(E_{\text{min}})$ at the magnetic field of SGR 1935+2154 ($\sim 2.2 \times 10^{14} \text{G}^7$) to the age $\geq 24\,\text{d}_{10}\,\text{kyr}$ and radio repetition-rate of SGR 1935. We then integrate eq. (4) and compare the resulting rate, a function of the three free parameters $\{B, \gamma, f_{\text{CCSN}}\}$, to the observed FRB rate (Bhandari et al. 2018). From the point of view of the all-sky rate alone, there exists a degeneracy between the number of FRB sources in the Universe ($\propto f_{\text{CCSN}}$) and the repetition-rate of each source (a function of $B$). However, this degeneracy can be broken by constraining the observed repetition rate of prolific repeaters.

Figure 5 shows, for values of the magnetic field $B(\gamma, f_{\text{CCSN}})$ required to fit the observed FRB rate (and its uncertainties), the region in $\{\gamma, f_{\text{CCSN}}\}$ parameter-space where the average repetition rate of the “active magnetar” population equals the observed repetition-rate of FRBs 121102 and 180916. For this, we take a fiducial value $\lambda_{\text{mag}}(> E_{\text{min}}) = 1\,\text{hr}^{-1}$ (see Fig. 1) however the uncertainties encompass a few orders-of-magnitude leeway in this assumed value. On the basis of Fig. 5 one can conclude that, regardless of the luminosity-function slope $\gamma$, fitting both the all-sky FRB rate and the activity level of repeating FRBs requires a rare class of progenitors, $f_{\text{CCSN}} \ll 1$. This is in line with many previous studies (e.g. Nicholl et al. 2017), and here we have extended these by adding the, possibly inevitable (though likely subdominant), contribution of a second population of “normal magnetars”, and utilizing scaling-relations anchored to the new observations of SGR 1935+2154.

The fact that $f_{\text{CCSN}} \ll 1$ is required of the “active population” implies that these sources cannot be interpreted as younger-incarnations of the SGR 1935+2154-like magnetar population as a whole, since this would require the same birth-rate for both populations, i.e. $f_{\text{CCSN}} \sim 0.1$. In the above we have assumed isotropic radio emission, as we expect beaming to be modest at most ($\lesssim$). If radio emission is beamed with some preferential directionality (as in pulsars) then the number of FRB emitting magnetars in the Universe may be larger than implied by the observed population. By “hiding” FRB sources this way, $f_{\text{CCSN}}$ may be pushed to larger values.

We note however that if bursts are instead beamed towards random directions, then the source birth rate as estimated above will be largely unchanged.

To further compare the resulting population against observational constraints, we calculate the expected...
number of repeating, and apparently-non-repeating, FRB sources detected by a mock survey of this population. We assume a limiting fluence of $F_{\text{lim}} = 4 \text{ Jy ms}$ and average repeat-field exposure time of $T_{\text{exp}} = 40 \text{ hrs}$, parameters motivated by the CHIME FRB survey. We then calculate the (Poissonian) number of sources for which only a single burst would be detected,

$$N_{\text{non-rep}} = \int dV(z) f_{\text{mag}} \Gamma_{\text{birth}}(z) \tau_{\text{active}} \mu e^{-\mu}$$  \hspace{1cm} (5)$$

where

$$\mu(z) \equiv \lambda_{\text{mag}} > 4\pi D_L(z)^2 F_{\text{lim}} T_{\text{exp}},$$  \hspace{1cm} (6)$$

and summing the contribution from both active and SGR 1935+2154-like populations. The number of sources classified as repeaters by the same survey is similarly calculated as

$$N_{\text{rep}} = \int dV(z) f_{\text{mag}} \Gamma_{\text{birth}}(z) \tau_{\text{active}} \left[ 1 - \frac{1}{2} \Gamma(2, \mu) \right]$$  \hspace{1cm} (7)$$

where $\Gamma(2, \mu)$ is the incomplete gamma-function.

Figure 6 shows $N_{\text{rep}}$ and $N_{\text{non-rep}}$ as a function of $\gamma$, and for a representative value of $f_{\text{CCSNe}} = 10^{-4}$ that is consistent with the constraints on FRB 121102-like activity and the all-sky FRB rate (Fig. 5). The number of detected repeating and non-repeating sources can be compared to values from the CHIME FRB survey, shown as horizontal curves (V. Kaspi, private communication). The figure shows that, for values $1 \lesssim \gamma \lesssim 1.5$, the absolute number and relative ratio of repeating and non-repeating FRBs can be reproduced simultaneously with the all-sky rate and per-source activity rate. At low values of $\gamma$ the observed FRBs are dominated by the less-active “ordinary magnetar” population. This results in a significant reduction in the relative number of repeating versus non-repeating sources that is inconsistent with observations. This substantiates our previous claim that a single population of (or equivalently, a population dominated by) SGR 1935+2154-like magnetars cannot account for the number of known repeaters.

Finally, using the cumulative distribution of detected events implied by eqs. (5,7), we calculate the characteristic distances at which repeating and non-repeating FRBs would be detected by this mock survey. The right panel of Fig. 6 shows the median distance of detected repeating and apparently-non-repeating FRB sources as a function of $\gamma$. Confirmed repeaters are detected on average at a lower distance, broadly consistent with the 149 Mpc distance of the first localized CHIME repeater (and note that FRB 121102, at a much larger distance of 972 Mpc is detected only once by CHIME, consistent with the median distance of apparently-non-repeating sources detected by the mock survey).

As the model shows, many potential rare magnetar formation channels could in principle be consistent with the all-sky FRB and repeater rate constraints (Fig. 5). One way to further break this degeneracy is via host galaxy demographics. A high-$B$ (and hence potentially particularly slowly rotating; Beniamini et al. 2020) tail of the magnetar population should be formed in otherwise ordinary CCSNe and hence track star-forming galaxies almost exclusively. Superluminous supernovae (SLSNe) and long-duration gamma-ray bursts (LGRB) should originate predominantly (Fruchter et al. 2006; Lunnan et al. 2015; Blanchard et al. 2016), though not exclusively (e.g. Perley et al. 2017), in dwarf star-forming galaxies. By comparison, NS mergers, white dwarf-NS mergers, and accretion-induced collapse (AIC) should originate from a range of star-forming and non-star-forming galaxies (Margalit et al. 2019), weighted more towards massive galaxies than SLSNe/LGRB. Attempts to perform an analysis along these lines are already underway (e.g. Margalit et al. 2019; Li & Zhang 2020), though it should be cautioned that without at least arcsecond localization, it is usually challenging to uniquely identify the host galaxy (Eftekhari et al. 2018), much less the local environment within the host galaxy as becomes available with VLBI localization (Bassa et al. 2017; Marcote et al. 2020).

4. IMPLICATIONS FOR MAGNETAR FRB MODELS

SGR 1935+2154 provides a clear link between FRBs and magnetars. Such a connection has been proposed and discussed extensively in the FRB literature well prior to this discovery (e.g. Popov & Postnov 2013; Lyubarsky 2014; Kulkarni et al. 2014; Katz 2016; Metzger et al. 2017; Beloborodov 2014; Kulkarni et al. 2014; Katz 2016; Metzger et al. 2017), leading to the development of several distinct magnetar models for FRBs. Broadly speaking, these models can be further divided based on whether the radio emission originates from near the NS magnetosphere (the “curvature”, “low twist”, and “reconnection” models) or at much further distances (“synchrotron maser blastwave” models). We also briefly discuss a couple NS-related models not specifically to magnetars. In the following, we discuss implications of the SGR 1935+2154 radio burst for these models, pointing out strengths and points of contention between each and the combined radio and X-ray observations.

4.1. Low Twist Models

In the low twist models (Wadiasingh & Timokhin 2019; Wadiasingh et al. 2020), magnetic field disloca-
4.2. Synchrotron Maser Blastwave Models

In synchrotron maser models, a version of which was first proposed by Lyubarsky (2014), FRBs are created via the coherent synchrotron maser process that is naturally produced in magnetized relativistic shocks (Galant et al. 1992; Plotnikov & Sironi 2019). Such shocks are expected to arise from relativistic flares that may be ejected during magnetar outbursts. A number of variants on the synchrotron maser model exist which differ regarding the nature of the upstream medium and the required shock properties; however, in all cases the bursts are powered by tapping into a small fraction of the kinetic energy of the outflow and predict corresponding (though differing) high-frequency counterparts to FRBs.

4.2.1. Magnetar Wind Nebula (Lyubarsky 2014)

Lyubarsky (2014) propose FRB production occurs as the ultra-relativistic flare ejecta collides with the pulsar wind nebula. The radius of the termination shock is estimated to be

\[
r_s = \sqrt{\frac{L_{\text{sd}}}{4\pi p c^2}},
\]

where \( p \) is the pressure inside the nebula. Taking \( L_{\text{sd}} \approx 1.7 \times 10^{34} \text{ erg s}^{-1} \) and \( p \sim 10^{-9} \text{ erg cm}^{-3} \) (estimated from the energy of \( 10^{51} \text{ erg} \) of a typical supernova and the observed \( \sim 20 \text{ pc} \) size of the supernova remnant...
surrounding SGR 1935+2154 (Kothes et al. 2018), we find \( r_s \approx 6 \times 10^{15} \) cm. The light crossing timescale to this radius is \( r_s/c \approx 2 \) day. However, because the flare ejecta and the resulting shock are also moving close to the speed of light, radio photons from the shocked nebula could in principle still arise nearly simultaneously with the X-rays, which in this model presumably must be generated from the inner magnetosphere.\(^8\)

Looking more closely at the predictions for the radio emission requires scaling the results of Lyubarsky (2014), who considered a giant flare which carries away a significant fraction of the magnetic energy of the star. The recent flare from SGR 1935+2154 was less energetic by a factor of \( \sim 10^6 \), corresponding to a strength of the magnetic field in the pulse smaller by a factor of \( \sim 10^5 \), i.e. dimensionless constant \( b \sim 10^{-3} \) in the notation of Lyubarsky (2014). Following equation (8) of Lyubarsky (2014) for these parameters, the predicted peak frequency of the maser emission from the forward shock is estimated to be \( \nu_{pk} \sim 10 \) MHz. Given the drop-off in the \( \nu L_\nu \) spectrum of the maser from \( \nu_{pk} \) to \( \sim 100 \nu_{pk} \) by a factor of \( \sim 10^{-4} \) (Plotnikov & Sironi 2019), the fraction of the total radio emission in the 1.4 GHz band of STARE2 would be only \( \sim 10^{-4} \). Given an intrinsic efficiency of the synchrotron maser emission of \( f_\xi \sim 10^{-2} - 10^{-3} \) (see next section), the resulting net efficiency of the radio emission of \( \sim 10^{-6} - 10^{-7} \) is at best marginally consistent with the observations if the energy of the flare ejecta were comparable to the released X-ray fluence.

4.2.2. Baryonic Shell (Metzger et al. 2019, Margalit et al. 2020)

In this version of the synchrotron maser model, first proposed by Beloborodov (2017), the ultra-relativistic head of the magnetar flare collides not with the magnetar wind nebula, but instead with matter ejected from a recent, earlier flare. Motivated by the inference from the radio afterglow of the 2004 giant flare from SGR 1806-20 of a slow ejecta shell generated by the burst (Gelfand et al. 2005; Granot et al. 2006), Metzger et al. (2019) consider the upstream medium to be a sub-relativistic baryon-loaded shell with an electron-ion composition.

The low efficiency of radio emission implied the X-ray and radio observations of SGR 1935+2154 (eq. 1) is consistent with predictions of this model. The radio inefficiency is attributable to a combination of the intrinsic synchrotron maser efficiency \( f_\xi \sim 10^{-2} - 10^{-3} \) (for moderate magnetization; Plotnikov & Sironi 2019) and a further reduction by a factor of \( \sim 10^{-2} \) due to the effects of induced-Compton scattering suppressing the low-frequency portion of the maser’s intrinsic SED (see Metzger et al. 2019, their \( \S3.2 \)).\(^9\)

Following the methodology of Margalit et al. (2020) we can use the energy, frequency, and duration of the observed radio burst to derive the intrinsic parameters of the flare demanded by the synchrotron maser model. Adopting the observed quantities from \( \S2 \), we find that the energy of the relativistic flare \( E_{\text{flare}} \): the Lorentz factor \( \Gamma \) of the shock gas at the time the observed radio flux is emitted; the radius of the shock from the central magnetar at this time, \( r_{sh} \); and the external density of the upstream baryonic shell at this location, \( n_{ext} \), are given by

\[
E_{\text{flare}} \approx 10^{40} \text{erg} f_\xi^{-4/5} \left( \frac{W}{5 \text{ ms}} \right)^{1/5} d_{10}^2, \tag{10}
\]

\[
\Gamma \approx 24 f_\xi^{-1/3} \left( \frac{W}{5 \text{ ms}} \right)^{-2/5} d_{10}^{1/3}, \tag{11}
\]

\[
n_{ext} \approx 9.3 \times 10^4 \text{ cm}^{-3} f_\xi^{-4/15} \left( \frac{W}{5 \text{ ms}} \right)^{2/5} d_{10}^{-2/3}, \tag{12}
\]

\[
r_{sh} \approx 1.7 \times 10^{11} \text{ cm} f_\xi^{-2/15} \left( \frac{W}{5 \text{ ms}} \right)^{1/5} d_{10}^{2/3}. \tag{13}
\]

In the above we express results in terms of the 1.4 GHz burst duration, \( W \), which we normalize to 5 ms motivated by the quoted CHIME burst width (Scholz & CHIME/FRB Collaboration 2020), in addition to the maser efficiency \( f_\xi = 10^{-3} f_{\xi,-3} \).

From our inferred parameters, the (very) local DM contributed by the immediate upstream medium ahead of the shock is \( DM \gtrsim n_{ext} r_{sh} \approx 5 \times 10^{-3} \text{ pc cm}^{-3} \), and can exceed this value significantly if the upstream medium extends to larger radii. In the context of the shock model, it may be expected that DM variations could exist between radio bursts on this order of magnitude or larger. Note however, that non-linear wave propagation effects of induced-Compton scattering suppressing the low-frequency portion of the maser’s intrinsic SED (see Metzger et al. 2019, their \( \S3.2 \)).\(^9\)

\(^8\) Although a burst of higher frequency (incoherent) synchrotron is predicted in this model from the shocked electrons, for parameters appropriate to SGR 1935+2154 this is predicted to occur at \( \gtrsim \text{GeV gamma-rays} \).

\(^9\) The value of \( f_\xi \) in general decreases with increasing values of the upstream magnetization, \( \sigma \). Based on 1D particle-in-cell simulations of electron-positron plasmas, Plotnikov & Sironi (2019) find an efficiency of

\[
f_\xi = 7 \times 10^{-4}/\sigma^2, \sigma \gg 1. \tag{9}
\]

Matching \( f_\xi = \pi \sim 10^{-5} \) (eq. 1) places a strict upper limit \( \sigma \lesssim 8 \). The true efficiency (and hence allowed \( \sigma \)) will be lower once accounting for 3D effects, and electron-ion composition of the upstream plasma (e.g. Iwamoto et al. 2019), and suppression of the radio signal from induced scattering by upstream electrons (Metzger et al. 2019). This scenario therefore requires an upstream plasma which is not highly magnetized.
interaction with the upstream plasma as well as strong upstream magnetic fields may inhibit the DM of this local environment (e.g. Lu & Phinney 2019).

The derived shock properties are shown in Fig. 7 in comparison to those derived for cosmological FRBs within the same model, for an assumed efficiency $f_\xi = 10^{-3}$. One important thing to note is that the flare energy $E_{\text{flare}}$ the model demands (based on the radio observation of SGR 1935+2154 alone) agrees remarkably well with the independently observed X-ray energy, $E_X \approx 8 \times 10^{39}$ erg. As we discuss below, such agreement is naturally expected if electrons heated at the shock generate the X-rays via synchrotron radiation in the fast-cooling regime.

Stated more directly, the model predicts a ratio (Margalit et al. 2019)

$$\eta_{\text{theory}} \equiv \frac{E_{\text{radio}}}{E_{\text{flare}}} = \left( \frac{1215}{512\pi^2} \left( \frac{m_e}{m_p} \right)^{1/5} \right)^{1/5} f_e^{1/5} f_\xi^{1/5} \left( \nu_{\text{obs}} \cdot t_{\text{FRB}} \right)^{-1/5} \sim 3 \times 10^{-5} \left( \frac{f_e}{0.5} \right)^{1/5} \left( \frac{1}{\nu_{\text{syn}} \cdot t_{\text{FRB}}} \right)^{1/5}, \quad (14)$$

which matches the observed ratio $\eta \equiv E_{\text{radio}}/E_X \sim 10^{-5}$ (eq. 1) for expected values of the maser efficiency $f_\xi \sim 10^{-3} - 10^{-2}$ (Plotnikov & Sironi 2019) provided that $E_X \sim E_{\text{flare}}$. In the above, $f_e$ is the ratio of electron to ion number densities in the upstream medium, and is $f_e \approx 1$ for an electron-ion plasma as we consider.

The same outwardly propagating shock that generates the coherent precursor radio emission (the “FRB”) in this scenario also generates incoherent synchrotron radiation from relativistically-hot electrons heated by the shock (Lyubarsky 2014; Metzger et al. 2019), somewhat akin to a gamma-ray burst afterglow. Using the shock parameters implied by the radio observations (Fig. 7), we now assess the predicted properties of the high-frequency counterpart, showing it to be in accord with the X-rays emission from SGR 1935+2154.

The peak frequency of the “afterglow” is set by the characteristic synchrotron frequency, which for an ultra-relativistic blastwave decelerating into an effectively stationary upstream medium of magnetization $\sigma = 10^{-1} \sigma_{-1}$ is given by (Metzger et al. 2019; their eqs. 56, 57)

$$E_{\text{peak}} \approx 50 \text{keV} \left( \frac{E_{\text{flare}}}{10^{39} \text{erg}} \right)^{1/2} \sigma_{-1}^{1/2} \left( \frac{t}{5 \text{ms}} \right)^{-3/2} \approx 160 \text{keV} \sigma_{-1}^{1/2} \left( \frac{W}{5 \text{ms}} \right)^{1/10} \left( \frac{t}{5 \text{ms}} \right)^{-3/2} d_{10}, \quad (15)$$

where $t$ is the time since the peak of the flare and we have assumed that 1/2 of the kinetic power dissipated at the shock goes into heating electrons into a relativistic Maxwellian distribution (supported e.g. by particle-in-cell simulations of magnetized shocks; Sironi & Spitkovsky 2011). In the second line of equation (15) we have substituted the flare energy from equation (13) needed to reproduce the radio burst properties from SGR 1935+2154. Although the value of $\sigma$ in the flare ejecta of a magnetar flare is uncertain theoretically, its value is nevertheless reasonably constrained: a minimum magnetization $\sigma \gtrsim 10^{-3}$ is required for the synchrotron maser to operate in the first place, while the declining efficiency of the maser emission with increasing $\sigma$ places an upper limit $\sigma \lesssim 1$. 

![Figure 7](image-url) Derived properties from the SGR 1935 radio burst within the variation of the synchrotron maser model in which the upstream medium is a baryon-loaded shell and adopting a fiducial value for the maser efficiency $f_\xi = 10^{-3}$ (see also Margalit et al. 2020). From top to bottom, the bulk Lorentz factor $\Gamma$, radius $r_{\text{sh}}$, and the external upstream density $n_{\text{ext}}$ of the shock at the time of the observed radio flare, all as a function of the derived total flare energy, $E_{\text{flare}}$. The flare energy, as derived from radio observations alone, is comparable to the detected X-ray counterpart of this burst (vertical dashed curve), in-line with predictions of the synchrotron maser model (§4.2.2) if the X-rays arise from thermal synchrotron radiation from the same shocks which generate the FRB.
For the same parameters, the cooling frequency is given by

$$
\nu_c \approx 13 \text{ keV} \sigma_{-1}^{-3/2} \left( \frac{n_{ext}}{10^4 \text{cm}^{-3}} \right)^{-3/2} \left( \frac{\Gamma}{100} \right)^{-4} \left( \frac{t}{10 \text{ ms}} \right)^{-2}
$$

$$
\approx 5.6 \text{ keV} \sigma_{-1}^{-3/2} \left( \frac{W}{5 \text{ ms}} \right)^{-1} \left( \frac{t}{5 \text{ ms}} \right)^{-1/2} d_{10}^{1/3}, \quad (16)
$$

where the particular temporal scaling $\propto t^{-1/2}$ is derived assuming a radially-constant density profile ($n_{ext} \propto r^0$).

The fact that $\nu_c \lesssim \nu_{syn}$ on timescales $t \sim 5 \text{ ms}$ of interest shows that the post-shock electrons are fast-cooling and hence a large fraction of the flare energy, $E_{flare}$, is emitted as hard X-rays of energy $E_{peak} \sim 10 - 100 \text{ keV}$. The predicted X-ray spectrum is thus fast-cooling synchrotron emission from relativistically-hot electrons with a thermal Maxwellian energy distribution (see Giannios & Spitkovsky 2009, their Fig. 3), resulting in an ordinary fast-cooling spectrum $\nu L_{\nu} \propto \nu^{1/2}$ between $\nu_c$ and $\nu_{syn}$ and an exponential cut-off at an energy $\sim \nu_{syn}$. Indeed, modeling of bright magnetar flares, suggests that they can be well fit by a cut-off power-law spectrum in the X-rays (van der Horst et al. 2012).

Extending the same model to the shock properties derived for the observed populations of cosmological FRBs predicts that the afterglow emission for these more energetic bursts will occur at much higher energies $E_{peak} \gtrsim \text{MeV-GeV}$ in the gamma-ray band (Fig. 8). Unfortunately, gamma-ray satellites like Swift and Fermi are generally not sensitive enough to detect this emission to the cosmological distances of most FRB sources (Metzger et al. 2019; Margalit et al. 2020; Chen et al. 2020). We furthermore emphasize that this predicted short ($\sim$millisecond duration) gamma-ray signal from the shocks is distinct from the longer-lasting and typically softer gamma-ray emission observed from giant Galactic magnetar flares (e.g. Palmer et al. 2005; Hurley et al. 2005), which is instead well explained as a pair fireball generated by dissipation very close to the NS surface. The latter being relatively isotropic compared to the relativistically-beamed radio emission from the ultra-relativistic shocks (hypothesized to accompany the beginning of the flare; Lyubarsky 2014; Beloborodov 2017) might explain the non-detection of FRB-like emission from the 2004 giant flare of SGR 1806-20 (Tendulkar et al. 2016).

If the X-rays from magnetar flares are attributable to thermal synchrotron shock emission, this may be imprinted in correlations between X-ray observables. Since electrons behind the shock are fast-cooling, the X-ray fluence $F_X$ should scale linearly with the flare energy $E_{flare}$, from which one predicts from equation (15) a correlation (for fixed $\sigma$)

$$
E_{peak} \propto F_X^{1/2} t_X^{-3/2}, \quad (17)
$$

between the spectral energy peak, burst fluence and some measure of the burst duration $t_X$.

For X-ray bursts from the Galactic magnetar SGR J1550-5418, van der Horst et al. (2012) report a correlation between the fluence and "emission" time, $\tau_0 \propto F_X^{0.47}$. Taking $t_X \propto \tau_0$ then equation (17) predicts $E_{peak} \propto F_X^{0.2}$, which is close to but slightly shallower than the correlation $E_{peak} \propto F_X^{-0.44}$ found by van der Horst et al. (2012) using the entire burst sample. However, note that the most energetic bursts studied by van der Horst et al. (2012) exhibit a flatter or even positive correlation of $E_{peak}$ with fluence. A correlation very close to $E_{peak} \propto F_X^{-0.44}$ is also predicted from equation (17) using the empirical relationship $F_X \propto t_X^{54}$ found between the bursts from different magnetars (Gavriil et al. 2004; see Fig. 2). Thus, we advance the radical hypothesis that hard X-ray emission in even ordinary magnetar flares can be generated by internal shocks in baryon-loaded outflows.

Scaling the shock model to the lower values of $r_{sh}, \Gamma$ than derived for SGR 1935+2154 above, would also have potential consequences for the X-ray spectrum. In particular, the synchrotron spectrum could in some X-ray

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**Figure 8.** The synchrotron maser model predicts that FRBs be accompanied by hard radiation counterparts, the properties of which can be derived by modelling the observed radio emission alone. Above, we show the peak energy of this counterpart as a function of flare energy, derived for a sample of cosmological FRBs and the SGR 1935+2154 radio burst, assuming a uniform magnetization $\sigma = 0.1$ for the upstream medium. The emitting electrons are fast cooling and therefore $E_{flare}$ roughly corresponds to the radiated fluence at $E_{peak}$. The observed $E_{peak}$ and fluence of the contemporaneous X-ray burst associated with SGR 1935+2154’s radio emission agree remarkably well with the model prediction.
counterparts of Galactic magnetar flares become opaque to pair creation. Following Lithwick & Sari (2001); Beniamini & Giannios (2017) we calculate the pair creation opacity corresponding to the model parameters described above, and find the external shock to be optically thin to pair creation. Pair creation could however become important for somewhat lower values of $r_{sh}, \Gamma$, which could be realized if the dissipation is due to internal shocks at a radius that is much lower than $r_{sh}$. For example, keeping $E_{\text{bare}}$ fixed and reducing the Lorentz factor to $\Gamma \sim 3$, will lead to a pair-creation cutoff at the internal shock site at $\sim 40$ keV. We speculate that this might explain why the “high temperature” of X-ray bursts described by a double black-body spectrum typically peak at energies $\lesssim 40$keV.

Finally, the explanation provided here for the X-ray spectra of Galactic magnetar short bursts might apply most robustly only to the smaller sub-set of bright SGR bursts which are luminous enough to drive radiation-driven outflows (i.e. large values of $L_{X}/L_{\text{min}}$, see Fig.3). In this regard it is interesting that the brightest bursts analyzed by van der Horst et al. (2012) exhibit a different correlation between their peak energy and flux to the rest of the bursts, consistent with the idea that the physical mechanism driving these bursts is different.

Returning to the radio burst emission, Metzger et al. (2019) predict a downwards drift in frequency as the shock decelerates and the (Lorentz boosted) synchrotron maser emission sweeps from high to low frequencies. The presence (or lack of) this feature in the SGR 1935+2154 burst would therefore provide a helpful diagnostic of FRB models and a probe of the density profile in this specific burst (see Margalit et al. 2020 for application to CHIME repeaters). In addition to the in-band drift that may potentially be detectable by CHIME (although the non-trivial frequency response of the CHIME sidelobes may hinder this), the same process could manifest as a small arrival time-delay between the STARE2 detection at 1.4 GHz and the CHIME detection at lower frequencies.

The relative delay between the observed radio emission (corrected for DM) and it’s hard-radiation counterpart observed at peak (Fig. 8) should be, at most, comparable to the radio burst duration ($\lesssim 5$ ms in the case of SGR 1935+2154’s April 28th burst). This results from the fact that the high-frequency photons are optically thin at the shock deceleration radius (when the emission peaks), while the radio is optically-thick to induced scattering at this time, and only escapes at a time $t \sim$burst-width later.

As shown in Figure 9, the shock model predicts that the X-ray emission should be accompanied by longer-lived synchrotron emission at lower frequencies as the shock propagates to larger radii, again similar to a GRB afterglow (Sari et al. 1998). For frequencies below $\nu_{\text{syn}}$ and $\nu_{c}$, the peak flux will rise as $F_{\nu} \propto \nu^{1/2}$ as $\nu_{\text{syn}} \propto \Gamma^{-\alpha}$ decreases in time until reaching the observing frequency, where $\alpha = 3/2$ during the relativistic phase and $\alpha = 3$ once the blastwave transitions to become non-relativistic. Thus, if $\nu_{\text{syn}}$ is passing through the X-ray band ($\nu_{X} \sim 10$ keV) on a timescale of $t_{X} \sim 0.1$ s, it will reach the optical band on a timescale of seconds and the radio band ($\nu_{R} \sim 10$ GHz) on a timescale of less than an hour. For an external medium with a radially constant density, the flux density $F_{\nu}$ at peak ($\nu_{\text{obs}} \sim \nu_{\text{syn}}$) is constant during the relativistic phase and thus approximately equal to that achieved initially at the higher frequencies. Using as a proxy for the latter the X-ray fluence of $F_{X} \sim 7 \times 10^{-7}$ erg/cm$^2$ of the FRB-generating flare from SGR 1935+2154, we predict a peak radio afterglow flux density $F_{\text{radio}} \sim F_{X}/(\nu_{X} \cdot t_{X}) \sim 0.3$ Jy (although self-absorption severely mitigates this estimate; see Fig. 9). After peak, the predicted flux will decay exponentially as the synchrotron emission occurs from electrons on the Wien tail of the thermal Maxwellian. Thus, such an afterglow is consistent with upper limits on radio afterglow emission of 0.05 mJy taken on a timescale of a few days (Ravi et al. 2020a,b). Also note

\[ \text{Figure 9. Optical R-band and 6/22 GHz radio flux due to thermal synchrotron afterglow emission of the X-ray/FRB-generated shock as a function of time in hours (bottom axis) as it propagates to larger radii. Shown for comparison are upper limits from Ravi et al. (2020a). In this simple estimate we have assumed a radially-constant density of the external medium; if the external medium does not extend far then the predicted flux would be lower than these estimates. Synchrotron self-absorption, which affects the radio light curves, has been included in an approximate way.} \]
that the radius sampled by the shock at these late times is a factor \(\gtrsim 30\) times larger than at the time of the earlier radio emission and there is no guarantee that the dense medium extends that far from the magnetar.

Finally, the ejection of the baryonic outflow is predicted to result in a small decrease in the spin frequency of the magnetar due to the temporary opening up of field lines by the mass-loaded wind (Thompson & Blaes 1998; Harding et al. 1999; Beniamini et al. 2020). The magnitude of the spin frequency change increases with the luminosity of the baryonic wind and its duration, both of which are highly uncertain. However if the X-ray burst concurrent with the FRB produced such an outflow, then there are at least two other bursts within the latest outburst, with even larger luminosities (Veres et al. 2020; Ridnaia et al. 2020b) that may have also produced an outflow. Taking for example the brightest of these bursts, that occurred on April 22nd, we can calculate a lower limit on the spin frequency decrease of \(\Delta \nu \approx \frac{2}{5} \times 10^{-8} \nu_{41}^{1/2} L_{34}^{1/2} \text{s}^{-1}\) (Beniamini et al. 2020).

4.2.3. Spin-Down Powered Wind (Beloborodov 2017, 2019)

Beloborodov (2017, 2019) argue that the upstream medium into which the relativistic flare collides is an electron/positron plasma from a spin-down powered component to the pulsar wind. Given the low spin-down power of SGR 1935+2154 however, this scenario might be somewhat disfavored.

The observed radio fluence at \(\nu = 1.4\, \text{GHz}\) in this model can be estimated from equation 91 of Beloborodov (2019), and re-expressed as a function of the spin-down power \(L_{\text{sd}}\), and pair multiplicity \(\mathcal{M}\),

\[
E_{\text{radio}} \sim 3 \times 10^{31} \text{erg} \frac{L_{\text{sd}}^{1/2} \mathcal{M}^{2/3}}{1}. \tag{18}
\]

In the above we have assumed the flare energy is \(10^{40}\) erg motivated by the X-ray counterpart of SGR 1935+2154, and we have omitted scaling with nuisance parameters for clarity. For the spin-down power of SGR 1935+2154 and standard pair-multiplicity of \(10^3\), this fluence is \(\sim\)three orders of magnitude lower than the observed energy of SGR 1935+2154’s radio burst.

This tension may be alleviated by an enhancement of the magnetar-wind (because of e.g. opening of field lines by the magnetar flare) or an increased pair-multiplicity shortly preceding the flare (Beloborodov 2019). From equation (18) we find that a pair-multiplicity of \(5 \times 10^7\) would be required to fit the observed fluence. This is much higher than pulsar pair multiplicities, though it has been suggested that much larger values \(\gg 10^3\) may be attainable for magnetars immediately preceding a flare (Beloborodov 2019).

The high pair-loading in this version of the synchrotron maser model, as in the Lyubarsky (2014) model, push the high-energy thermal synchrotron counterpart to lower frequencies (\(\nu_{\text{syn}} \propto f_e^{-2}\)), leading to an “afterglow” peaking optical/UV band (Beloborodov 2019) instead of the x-ray/gamma-ray band predicted in the baryonic model (Fig. 8). In this scenario, as in the magnetar wind nebula case (§4.2.1), the X-rays from the flare must be created by a process which is not directly related to the FRB mechanism.

4.3. Additional Models

In curvature models, the FRB is produced by curvature radiation from bunched electrons streaming along the magnetic field lines of the magnetar (e.g. Kumar et al. 2017; Lu & Kumar 2018). These models predict fluence ratios \(\eta \sim 1\) in all bands (Chen et al. 2020), and thus cannot explain properties of the observed X-ray burst of SGR 1935+2154 (whose fluence ratio is \(\eta \sim 10^{-5} \ll 1\), but also in terms of X-ray spectrum) as a bona fide FRB counterpart. This shortcoming can potentially be dismissed by arguing that the same magnetar activity leading to particle bunching, acceleration, and FRB emission, also produces “normal” short X-ray bursts. However, this scenario makes no prediction as to the quantitative relationship between the radio and X-ray burst properties, and the observed fluence ratio of \(\eta \sim 10^{-5}\) is ad-hoc within this framework. These considerations apply also to models where FRBs are produced by reconnection in the outer magnetosphere (Lyubarsky 2020), or indeed to any magnetospheric models. If true, a testable prediction of the scenario (and one that would be in tension with synchrotron-maser models) may be large variations in the value of \(\eta\) for future events.

Another class of FRB models discussed in the literature power FRBs by the kinetic energy of an outflow interacting with the magnetosphere of a NS (Zhang 2017, 2018; Ioka & Zhang 2020). The outflow in these “cosmic comb” models has been suggested to range from AGN-driven winds, to GRB jets, or winds from a binary companion to the NS. None of the above are likely to be applicable in the context of SGR 1935+2154’s radio burst, in tension with predictions of this model (although see Wang et al. 2020).

A final class of NS-related models we discuss are “spin-down models”, in which the radio bursts are powered by rotational energy of the NS (Cordes & Wasserman 2016; Connor et al. 2016; Muñoz et al. 2020). Though in principle applicable to magnetars, these models typically envision normal pulsars as progenitors. Indeed, considering the very low spin-down power of SGR 1935+2154 in comparison to pulsars, and the fact that the latter are \(\gtrsim 100\) times more common than Galactic magnetars (in terms of their effective active lifetime), it seems unmotivated...
eral that a spin-down-powered “FRB” would be first detected for SGR 1935+2154. A prediction of this model would be a change in NS spin period due to the released burst energy. Accounting for the radiated energy of SGR 1935+2154’s burst, including its associated X-ray counterpart, we find that a change $\Delta \Omega \approx -4 \times 10^{-6} \text{s}^{-1} \text{d}^{-1}$ in the angular velocity of SGR 1935+2154 need to have occurred. A reduction in the spin frequency is also expected in the Metzger et al. (2019) version of the synchrotron maser model due to opening of magnetic field lines by the baryonic outflow, however this effect is much smaller ($\lesssim 10^{-6}$). The Beloborodov (2019) synchrotron maser model (§4.2.3) also necessitates some level of period change due to a significant enhancement of pulsar-wind required immediately preceding the FRB, however this too would be expected to be smaller than $\Delta \Omega$ estimated above. Future timing of SGR 1935+2154 may help test this prediction of the spin-down model.

5. CONCLUSIONS

We have explored implications related to the population of FRB sources and to theoretical models of FRBs in light of the recent detection of a luminous millisecond radio burst from the Galactic magnetar SGR 1935+2154 (Scholz & CHIME/FRB Collaboration 2020; Bochenek et al. 2020a). The large energy of this burst makes it unique amongst any previously observed pulsar/magnetar phenomenology, and bridges the gap to extragalactic FRBs (Bochenek et al. 2020a).

Our conclusions may be summarized as follows. With regards to general implications for extragalactic magnetar populations:

- Broadly speaking, the discovery of a highly luminous millisecond-duration radio burst coincident with the X-ray flare of the Galactic magnetar SGR 1935+2154 supports magnetar models for extragalactic FRBs.

- The X-ray properties of the flare are fairly typical of Galactic magnetar flares in terms of fluence and overall duration (Fig. 2), however it’s X-ray spectrum may have been harder than usual (Mereghetti et al. 2020b). Furthermore, with the notable exception of the giant flare from SGR 1806-20, relatively few such flares would have previously been detected at radio wavelengths for a similar low ratio $\eta \equiv E_{\text{radio}}/E_{\text{X}} \sim 10^{-5}$ of radio to X-ray fluence (Fig. 3). This suggests that a sizable fraction of Galactic magnetar flares may be accompanied by luminous radio bursts, although we caution that multiple emission mechanisms may be at play in producing magnetar X-ray flares, and that only the subset produced by shocks would be expected to emit coherent radio bursts.

- Applying the same fluence ratio $\eta$ to giant magnetar flares would imply that Galactic magnetars are capable of powering even the most energetic cosmological FRBs (Fig. 1). However, a stark discrepancy exists between the activity (burst repetition rate) of Galactic magnetars and the sources of the recurring extragalactic FRBs. If universal, the low efficiency $\eta \sim 10^{-5}$ also places strong upper limits on the magnetar active lifetime in the latter case, much shorter than the ages of Galactic magnetars (eq. 2).

- The estimated rate of radio bursts similar to that observed from SGR 1935+2154 is insufficient to contribute appreciably to the observed extragalactic FRB rate (eq. 3). Depending on the luminosity function of the Galactic flares, the all-sky FRB rate (including also giant flares) can be reproduced by “ordinary” Galactic magnetars similar to SGR 1935+2154 (Fig. 4). However, such a model fails to simultaneously explain the large (per-source) repetition rate of known repeaters or the large DMs of the FRB population.

- Instead, considering a two-component model—we add a second population of magnetars whose birth-rate is a free-parameter, and whose activity level and lifetime are scaled from SGR 1935+2154 as a function of the population’s magnetic field strength. This model allows to broadly replicate the observed properties of the FRB population (Fig. 6), however only if the birth-rate of the “active” magnetar population is $\ll$ than the CCSN rate (Fig. 5; in line with previous work, e.g. Nicholl et al. 2017).

- This implies that the population of “active” magnetars cannot be interpreted as an earlier evolutionary state of SGR 1935+2154-like magnetars which are born in a large fraction of CCSNe. Instead this population may form through more exotic channels such as SLSNe, AIC, or binary NS mergers (Metzger et al. 2017; Margalit et al. 2019).

In addition to the general implications summarized above, we also address implications for specific FRB magnetar models. We stress that there is no single “magnetar model” for FRBs, and that many distinct models have been suggested in the literature, and these differ in the requisite magnetar properties, the FRB emission mechanism, and predictions for (of lack of)
multi-wavelength counterparts (§4). In this context, we find that:

- Magnetospheric models (“curvature”, “low twist”, and “reconnection” models) predict either no high-energy counterpart, or weak counterparts of comparable energy to the radio emission ($\eta \sim 1$). This is in tension with the observed X-ray counterpart in SGR 1935+2154, where $\eta \sim 10^{-5}$. This shortcoming can be dismissed by interpreting the X-ray counterpart as a “normal” short X-ray burst. However this scenario makes no predictions of the spectral or energetic properties of the X-ray flare and the $\eta \sim 10^{-5}$ radio-to-X-ray fluence ratio is ad-hoc within this framework (§4.3).

- Synchrotron maser models, which involve relativistic flare ejecta colliding with an external medium, provide a promising alternative. However, these models differ in the nature of the upstream medium and their predicted multi-wavelength afterglow.

- Models in which the upstream is the magnetar wind nebula (Lyubarsky 2014; §4.2.1) may have an efficiency issue and predict associated afterglow in the GeV range. Likewise, models in which the upstream is a rotational-powered pulsar wind (Beloborodov 2017, 2019) are strained and predict a lower frequency counterpart (§4.2.3).

- The baryonic shell version of the synchrotron maser shock model naturally explains the value of $\eta$ (compare eqs. 1 and 14) in addition to the timing and spectral features of the observed X-ray emission (Fig. 8). The model requires substantial mass ejection to accompany the flares, which may be in tension with the relatively low luminosity of the flares if the outflows are driven by radiation pressure (Fig. 3). On the other hand, the requirement for mass ejection—and the sensitivity of the radio emission to the detailed properties of the upstream medium—could help explain why not all magnetar flares are accompanied by a luminous FRB.

- The latter model suggests a new paradigm in which X-ray emission of magnetar flares arises from thermal synchrotron radiation from internal shocks. This model predicts a power-law spectrum with an exponential cut-off, and correlations between the peak energy of the burst and other burst properties (e.g. duration and fluence), which are broadly consistent with observations (van der Horst et al. 2012).

- The baryon shell synchrotron maser shock model (Metzger et al. 2019; Margalit et al. 2020) makes several predictions testable by future Galactic or extragalactic FRBs: (1) Although X-ray/gamma-ray emission can arise from magnetar flares without an accompanying FRB (e.g. if the X-rays/gamma-rays do not arise from shocks), the opposite is not true. Any FRB-like burst should be accompanied by X-ray/gamma-ray emission with an energy at least a factor $\eta^{-1} \gtrsim 10^4$ larger than the emitted radio energy (eq. 14); (2) scaling up to cosmological FRBs, the equivalent prompt synchrotron counterpart should peak in the $\gtrsim$ MeV-GeV gamma-rays band (Fig. 8); (3) Galactic FRBs may be accompanied by longer lived optical/radio emission on a timescale of seconds/minutes (Fig. 9), the details of which however depend on the extent of the external medium surrounding the magnetar on larger radial scales than probed by the hard X-rays.

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Note that the X-rays and radio are predicted to arrive contemporaneously in this model, contrary to arguments made by Mereghetti et al. (2020b), who did not account for relativistic time-of-flight effects.
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