Prediction for the Multi-band Afterglows of FRB 200428 and its Implication (Postprint)

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Abstract

The physical mechanism of fast radio bursts (FRBs) is still unknown. On 2020 April 28, a special radio burst, FRB 200428, was detected and believed to be associated with the Galactic magnetar SGR 1935+2154. It confirms that at least some of the FRBs were generated by magnetars, although the radiation mechanism continues to be debated. To this end, we study in detail the multiband afterglows of FRB 200428 described by the synchrotron fireball shock model. We find the prediction for the optical and radio afterglows of FRB 200428 is consistent with the observations when considering the post-FRB optical and radio upper limits from the literature. We also show that the follow up detection of the afterglows from fast radio bursts like—FRB 200428 is possible at the radio band, though challenging. Based on our model, one can obtain information about the energy of the fireball, the radiation zone, and the nature of the surrounding medium. That may shed light on the physical mechanism of FRBs.

Full Text

Preamble

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Prediction for the Multi-band Afterglows of FRB 200428 and its Implication

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Abstract

The physical mechanism of fast radio bursts (FRBs) remains unknown. On 2020 April 28, a special radio burst, FRB 200428, was detected and associated with the Galactic magnetar SGR 1935+2154. This discovery confirms that at least some FRBs are generated by magnetars, although the radiation mechanism continues to be debated.

In this work, we study in detail the multi-band afterglows of FRB 200428 using the synchrotron fireball shock model. We find that our predictions for the optical and radio afterglows are consistent with observational upper limits reported in the literature. We also show that follow-up detection of afterglows from FRBs like FRB 200428 is possible in the radio band, though challenging. Based on our model, one can obtain information about the fireball energy, radiation zone, and nature of the surrounding medium, which may shed light on the physical mechanism of FRBs.

Key words: stars: magnetars – (stars:) gamma-ray bursts: general – radiation mechanisms: non-thermal

1. Introduction

Fast radio bursts (FRBs) are cosmological radio transient sources whose physical origins remain debated (e.g., Cordes & Chatterjee 2019; Petroff et al. 2019; Zhang 2020; Xiao et al. 2021). On 2020 April 28, a bright millisecond radio burst from the Milky Way magnetar SGR 1935+2154 was detected simultaneously by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the Survey for Transient Astronomical Radio Emission 2 (STARE2; e.g., Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020). With an energy of 10^{35} erg, it is considered likely to be an extension of extragalactic FRBs at the low-energy end (e.g., Lu et al. 2020). If this radio burst is indeed an FRB (FRB 200428), it directly confirms that at least some FRBs are produced by magnetar flares (e.g., Lyubarsky 2014; Beloborodov 2017; Margalit et al. 2018; Metzger et al. 2019).

Due to more comprehensive data from repeating FRBs, several theoretical models have been proposed to explain the FRB generation mechanism. Beloborodov (2017) explains the mechanism of repeating FRBs by suggesting that a young magnetar releases energy from successive flares, which are driven by accelerated ambipolar diffusion in the neutron star core and then power nebula particles to produce bright millisecond bursts. The energy supply from successive flares and collisions between different flares give rise to a series of repeating FRBs with varying intervals. This powerful shock wave can also produce bright optical radiation (e.g., Beloborodov 2020). Yang et al. (2019) studied the brightness and detection prospects of "fast optical bursts" (FOBs) associated with FRBs, indicating that it is possible to detect associated FOBs through special inverse Compton scattering processes and with high-sensitivity telescopes. However, Waxman (2017) placed strict constraints on the nature of the persistent source and found that the typical magnetar wind nebula model is inconsistent with predictions, leading them to propose a strong synchrotron maser emission mechanism adapted to the GHz band.

Metzger et al. (2019) suggested that repeating FRBs might be formed by the magnetar-powered synchrotron maser shock model, where the central engine releases clean ultrarelativistic magnetized shock waves that spread outward and then collide with upstream mildly relativistic magnetized ion-electron shells. The shell decelerates through reverse and forward shock waves, with the latter producing the observed FRBs via synchrotron maser mechanism. Similar to GRB afterglows, the forward shock also heats electrons to extremely relativistic temperatures, powering incoherent synchrotron X-ray/gamma-ray emission. Recently, Cooper et al. (2022) predicted the multi-band afterglow of FRB 200428 based on the magnetar-powered synchrotron maser shock model. The mechanism of FRB 200428 may be consistent with this previously predicted model, but due to its lower luminosity, the energy distribution may be slightly different (e.g., Wang et al. 2020).

Another observational breakthrough for FRB 200428 was the simultaneous detection of an associated X-ray burst, with a radio-to-X-ray energy ratio of 10^{-5} (e.g., Mereghetti et al. 2020; Li et al. 2021; Ridnaia et al. 2021; Tavani et al. 2021). Remarkably, the far-away model had predicted the occurrence of X-ray bursts associated with FRBs, as well as the low radiation efficiency of FRBs (10^{-5}), which was well verified in the case of FRB 200428 (e.g., Margalit et al. 2020). However, Wu et al. (2020) found that the ejected baryonic matter of the magnetar, mainly provided by the crust, is higher than the typical mass of a magnetar's outer crust. This finding indicates that the outer crust of the magnetar in their model cannot physically eject enough baryonic mass. We note that the mechanism and rate of baryonic mass ejection remain uncertain, thus requiring further observational and theoretical investigations. The close-in model can also account for the low radiative efficiency of FRB 200428 and its associated X-ray bursts, although these were not predicted by the model (e.g., Lu et al. 2020).

Surprisingly, despite numerous X-ray bursts during the active period of SGR 1935+2154, no other FRB events have been detected so far except for FRB 200428 (e.g., Lin et al. 2020; Bailes et al. 2021; Kirsten et al. 2021). One notes that the spectrum of the X-ray burst associated with FRB 200428 appears much harder than other bursts, with a peak energy of 85 keV (e.g., Ridnaia et al. 2021). This may imply that the X-ray burst associated with FRB 200428 was unusual, and FRBs are produced only in this kind of burst. This leads to speculation that this may be the underlying reason why other X-ray bursts do not have FRB associations. As suggested by Ioka (2020), usual X-ray bursts could come from fireballs trapped in the closed field lines of the magnetar, analogous to the standard model for soft gamma-ray repeaters (SGRs; e.g., Thompson & Duncan 1995, 2001; Kaspi & Beloborodov 2017). However, the X-ray burst associated with FRB 200428 may come from a trapped-expanding fireball located in the open field line region of the magnetar (e.g., Ioka 2020). The observed temperature of such an expanding fireball remains constant due to relativistic effects, which is consistent with the burst having a larger E 85 keV than usual bursts.

As seen in the physical picture above, X-ray bursts associated with FRBs could be accompanied by energetic ejecta (the expanding fireballs), while usual X-ray bursts are not. According to the standard fireball model, a pair of shocks will be generated when the fireball sweeps the surrounding medium, including the reverse shock that propagates through the ejecta and the forward shock that propagates through the surrounding medium. Similar to the case of gamma-ray bursts (GRBs), these shocks would produce multi-band afterglows (e.g., Yi et al. 2014). The evolution of the afterglows is closely related to the fireball energy and the nature of the surrounding environment (e.g., Yi et al. 2014; Zhang 2014).

Therefore, if FRB 200428 repeats in the future and its multi-band afterglows are observed, it will provide new insights into the physical mechanism of FRBs. In this work, we study in detail the multi-band afterglows of FRB 200428 and their detectability. Many models attempt to explain the origin of FRBs, and it is too early to determine which is correct given the current observational evidence. Therefore, we do not discuss the framework of any specific FRB model. Instead, we refer to the GRB afterglow model and use a memoryless fireball to calculate FRB afterglows. Based on such a model-independent afterglow framework, we can predict the timescale and brightness of potential future afterglows of FRB 200428 using only a few constrained parameters, providing a theoretical basis for afterglow observations. Conversely, future afterglow observations can be used with our model to make model-independent constraints on the surrounding environment of FRB 200428, which is critical for revealing its physical mechanism.

This work is organized as follows. The standard afterglow external shock model is described in Section 2, and the results of multifrequency afterglows for FRB 200428 are presented in Section 3. Discussion and conclusions are given in Section 4.

2. The Model

Following Yi et al. (2014), we apply the standard GRB afterglow external shock synchrotron emission model (e.g., Mészáros & Rees 1997; Sari et al. 1998; Gao et al. 2013; Yi et al. 2014) to FRBs. This model describes the interaction between the outflow and ambient medium, with several free parameters: total kinetic energy E, ambient medium density n_0, initial Lorentz factor Γ, shock energy equipartition parameters and _B for electrons and magnetic fields respectively, and electron injection spectral index p. If both forward and reverse shocks are considered, the equipartition parameters and p may differ between shocks, leading to nine parameters total.

We primarily consider forward shock (FS) emission. However, it is uncertain whether reverse shock (RS) emission appears, which depends on the outflow magnetization parameter σ—the ratio between Poynting flux and matter flux (e.g., Zhang & Kobayashi 2005; Mimica et al. 2009; Mizuno et al. 2009). Considering that FRB 200428 originates from SGR J1935+2154, the outflow may be magnetized. As shown in previous studies (e.g., Komissarov et al. 2009; Granot et al. 2011), the outflow is accelerated by magnetic pressure gradient, σ decreases with radius, and Γ increases with radius. Additionally, significant magnetic dissipation occurs during the FRB emission phase. Therefore, σ has substantial uncertainty. If it is already below unity, RS emission must be expected (e.g., Zhang et al. 2003; Zhang & Kobayashi 2005; Yi et al. 2014).

For simplicity, we consider only standard synchrotron emission, which is mainly determined by bulk Lorentz factor Γ and total kinetic energy E, neglecting other complicating factors. Under this model, light curve evolution is associated with three characteristic frequencies: minimum synchrotron frequency _m, cooling frequency _c, self-absorption frequency _a, and the spectral peak flux (e.g., Gao et al. 2013; Yi et al. 2014). The transition to the non-relativistic phase occurs when $\Gamma - 1 = 1$. For FRB 200428 afterglow, the transition time in the non-relativistic phase is roughly t_N 306.1 s and 659.5 s for $E = 10^{40}$ and 10^{41} erg, respectively.

Although the surface dipolar magnetic field strength of magnetar SGR J1935+2154 is around B_p 10^{14} G, the radiation efficiency of FRBs in the radio band is low, and the isotropic energy of FRBs may be about 5–6 orders of magnitude less than the total energy. Based on observations, the isotropic energy of FRB 200428 is about 10^{35} erg; therefore, we adopt total kinetic energies of $E = 10^{40}$ and 10^{41} erg in this work.

Additionally, we adopt a conservative bulk Lorentz factor of $\Gamma = 50$ for FRB 200428. Even if we set the Lorentz factor to 100, the brightness of the multi-band afterglows changes negligibly (e.g., Falcke & Rezzolla 2014; Katz 2014). The deceleration time is much shorter than for typical GRBs; using parameters $E = 10^{41}$ erg, $n_0 = 1$ cm^{-3}, and $\Gamma = 50$, the deceleration time of FRB 200428 is approximately 0.1 s.

Based on standard assumptions (e.g., Sari et al. 1998; Wu et al. 2003; Gao et al. 2013; Yi et al. 2013, 2014, 2020), we calculate FRB afterglow emissions. As FRB 200428 is a Galactic transient with a luminosity distance of 10 kpc (e.g., Zhong et al. 2020), the FS emission of FRB 200428 at shock crossing time t_× can be expressed with ,f = 0.1, _B,f = 0.01, and p = 2.5. Due to the lower total energy of FRBs compared to GRBs, the outflow rapidly reaches the non-relativistic phase. Because the outflow is magnetized, we normalize _B,r to 0.1.

2.1. Results

Theoretical multi-wavelength afterglows of FRB 200428 are shown in Figures 1 and 2. Figure 1 [Figure 1: see original paper] shows FS afterglow light curves of FRB 200428 in X-ray (2 keV, panel (a)), optical (R-band, panel (b)), and radio (1 GHz, panel (c)) bands. Considering different emission efficiencies, we adopt two kinetic energy values: E = 10^{40} erg (black) and 10^{41} erg (blue). Other parameters are set to typical values: $\Gamma = 50$, $n_0 = 1$ cm^{-3}, ,f = 0.1, _B,f = 0.01, and p = 2.5. We also plot sensitivity lines for four different detectors in various energy bands, following our previous study (e.g., Yi et al. 2014). The red dashed line in panel (a) shows the Swift/XRT detector sensitivity, which scales as t^{-1} to $t^{-1}/^{2}$ when F_ = 2.0×10^{-15} erg cm^{-2} s^{-1} at t = 10^5 s (e.g., Moretti et al. 2009; Yi et al. 2014). The green dashed line in panel (a) shows the Insight-HXMT sensitivity, which scales as t^{-1} for arbitrarily long exposure times. The red dashed line in panel (b) shows the Large Synoptic Survey Telescope (LSST) sensitivity. In survey mode, LSST reaches 24.5 mag in 30 s. The red dashed line in panel (c) shows the Expanded Very Large Array (EVLA) sensitivity, which scales as $t^{-1}/^{2}$ for arbitrarily long exposure times.

As shown in Figure 1 panel (a), the X-ray afterglow of FRB 200428 is too faint; theoretically, neither Swift/XRT nor Insight-HXMT can detect it. Although the first X-ray counterpart of FRB 200428 was observed, Insight-HXMT implemented long-term observations of SGR J1935+2154 since then, detecting no X-ray counterparts from FRB 200428—only hundreds of short X-ray bursts triggered by Insight-HXMT and other satellites (e.g., Cai et al. 2022). In the optical R-band (panel (b)), the peak magnitude is about 16 and 13.6 for energies E = 10^{40} and 10^{41} erg, respectively. The LSST sensitivity line is below the peak magnitude. However, due to the very early peak time of 0.2–0.4 s, LSST cannot follow up quickly enough. For optical bands, counterpart emission may still be detectable if follow-up observations are performed within a few hundred seconds after the FRB. In the 1 GHz radio band (panel (c)), the peak flux density is about 1.46×10^{-3} and 1.46×10^{-2} Jy, with peak times of 5.7×10^{2} and 1.2×10^{3} s for the two kinetic energies, respectively. This might be caught by EVLA if followed up early. Regrettably, EVLA did not detect this source during this period. As reported by Bailes et al. (2021), the MeerKAT radio telescope began pointing to the source 4×10^{4} s after FRB 200428 triggered but detected no signals, due to either rapidly declining FS emission or diffuse emission around the magnetar. Compared to other energy bands, radio afterglows from FRBs are the most promising for detection, mainly because they last much longer. Therefore, if we are fortunate enough to detect another bona fide FRB like FRB 200428, rapid radio observations on timescales of minutes to hours will provide the best opportunity to observe afterglows.

RS emission for FRB 200428 is also shown in Figure 2 [Figure 2: see original paper]. Fixing other parameters, we adopt total energy $E = 10^{41}$ erg and _B,r = 0.16. In general, the RS afterglow of FRB 200428 is more difficult to detect with current detectors, as the emission is either too faint or peaks too early. As shown in Figure 2, like FS emission, the RS X-ray afterglow (panel (a)) is too faint, while the optical R-band peaks so early (t_p   0.1 s) that LSST cannot follow up. Additionally, the 1 GHz radio band (panel (c)) reaches peak flux early (33 s) but declines rapidly.

According to Cooper et al. (2022), who provided light curves using the method from Margalit et al. (2020) and applied BOOTES-3 upper limits to significantly constrain FRB afterglows, the optical flux limit scales as F_{limit} $t^{-1}/^{2}$ starting from early observations (orange line). Using the same energy $E = 1 \times 10^{43}$ erg in our afterglow model, our estimated results (green line in panel (b) of Figure 1) nearly reach the optical upper limits. Our optical results are consistent with predictions from Cooper et al. (2022). To better illustrate how optical peak flux depends on E and n_0, we show the contour of optical peak flux in the E–n_0 plane in Figure 3 [Figure 3: see original paper]. We set _B,f = 0.01,   = 0.1, $p = 2.5$, and $\Gamma = 50$, with energy ranging from 10^{40}–10^{43} erg and n_0 ranging from 10^{-3}–10^{3} cm^{-3}. The reasonable parameter space for FRB 200428 may be reflected by optical observation upper limits from the peak flux contour. As shown in the figure, the black line represents the limitation on model parameter space imposed by the BOOTES-3 observation upper limit. The contour clearly shows that only when the environment around FRB 200428 is dense enough can sufficiently bright radio afterglows be produced.

3. Summary and Discussion

In this work, we applied the standard GRB afterglow external shock synchrotron emission model to the peculiar case of FRB 200428 and calculated its multi-wavelength afterglows. We found that due to its low energy, the broadband afterglows of FRB 200428 are very faint. Even so, current detectors may be able to follow up and detect its broadband afterglows, particularly at radio wavelengths.

The X-ray afterglow from FS is so weak and decays rapidly after peaking that current detectors cannot easily catch it. This may require a wide-field X-ray telescope (such as Einstein Probe or Lobster) to have a chance of capturing the X-ray afterglow of FRB 200428 when it repeats. For the optical afterglow, current detectors could theoretically detect it, but rapid follow-up is difficult due to the early peak and fast decay. The most promising afterglow of FRB

200428 is found in the radio band, although the radio afterglow flux only reaches the mJy level. Thanks to the relatively late peaking time of the radio afterglow (10^3 s), if radio telescopes can slew to the source position within an hour, there is a good chance of detection. In general, follow-up detection of FS afterglows from FRB 200428 is plausible, though challenging.

In contrast, RS afterglows are almost impossible to detect with current detectors, as the emission is either too weak or peaks too early. Given the difficulty of rapid follow-up observations, a strategy of long-term monitoring when SGR 1935+2154 enters an active phase may be adopted. This approach offers a much greater chance of catching an afterglow but requires significantly more observation time.

Cooper et al. (2022) also estimated multi-wavelength afterglows of FRB 200428 based on the Metzger et al. (2019) model, providing results from LOFAR imaging observations of SGR 1935+2154. Due to its low luminosity, the predicted multi-band afterglows from FRB 200428 remain too faint for detection, placing some radio and optical upper limits on afterglow emissions (also seen in our results). Considering the similarity of early afterglow models, our results are very consistent with Cooper et al. (2022), especially when using the same parameters for this burst. In any case, once afterglows from FRBs like FRB 200428 are observed in the future, the early afterglow model can provide information about fireball energy, radiation zone, and surrounding medium properties, which may shed light on the physical mechanism of FRBs.

Interestingly, since 2022 October 10, SGR J1935+2154 has been active again (e.g., Ryder et al. 2022), and a radio burst associated with an X-ray burst was detected (e.g., Dong & CHIME/FRB Collaboration 2022; Wang et al. 2022), providing another case demonstrating that magnetars can drive FRBs. Four FAST observations have been conducted on SGR J1935+2154 to search for additional FRB-magnetar burst associations and radio pulsations (e.g., Zhu et al. 2020), but no pulses were detected. We also proposed four simultaneous NICER observations on SGR J1935+2154 with FAST to cover possible magnetar bursts in soft X-ray and search for correlated radio/X-ray pulsations, but again no pulses were detected. On 2022 October 22, a radio burst was detected from the S-band 40 m Yunnan telescope, CAS (e.g., Huang et al. 2022). No counterpart was detected at this stage, confirming that follow-up detection of multi-band afterglows from FRBs remains challenging.

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