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Searching for radio pulsation from SGR 1935+2154 with the Parkes ultra-wideband low receiver

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Abstract: Magnetars have been proposed to be the origin of the fast radio bursts (FRBs) soon after its initial discovery. The detection of the first Galactic FRB 200428 from SGR 1935+2154 has made this hypothesis more convincing. In October 2020, this source was supposed to be in an extremely active state again. We then carried out a 1.6-hours follow-up observation of SGR 1935+2154 using the new ultra-wideband low (UWL) receiver of the Parkes 64 m radio telescope covering a frequency range of 704–4032 MHz. However, no convincing signal was detected in either of our single pulse or periodicity searches. We obtained a limit on the flux density of periodic signal of 3.6 μJy using the full 3.3 GHz bandwidth data sets, which is the strictest limit for that of SGR 1935+2154. Our full bandwidth limit on the single pulses fluence is 35 mJy ms, which is well below the brightest single pulses detected by the FAST radio telescope just two days before our observation. Assuming that SGR 1935+2154 is active during our observation, our results suggest that its radio bursts are either intrinsically narrow-band or show a steep spectrum.

Keywords: magnetars; fast radio bursts; soft gamma-ray repeater

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1 Introduction

Fast radio bursts (FRBs) are one of the most energetic sources in the universe with luminosities up to 10^{39} erg s^{-1}. Since the original discovery in 2007[1], efforts to explore the physical origin of FRBs have continued. Several important progress has been made in the last few years, including the localization for host galaxy and detection of periodic activities[2,3]. FRB 200428, a Galactic FRB event detected by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) and the Survey for Transient Astronomical Radio Emission 2 (STARE2), is another breakthrough in revealing the mystery of FRB origin[4,5]. Considering the dispersion delay, the two X-ray components of the magnetar burst occur within 3 ms of the radio burst components[6].

Magnetars have been proposed to be the origin of FRBs[7] soon after its initial discovery. A large number of papers discussed this model from different perspectives[8,9]. The detection of FRB 20048 shows that magnetars are able to generate bright radio bursts with luminosity close to FRBs. However, extreme activities of some FRBs (e. g., FRB 121102[10]) are still not understood and most of the FRBs are much more energetic than FRB 200428. There are generally two types of coherent radio emission models, those originating in the magnetospheres and those produced by relativistic shocks[11]. Such models can explain the energy ratio of FRB 200428 and its associated X-ray burst (XRB), but the magnetosphere origin has already been well established to explain the XRBs of magnetars and are currently the most promising models for FRB 20048-like events.

Magnetars are a small group of neutron stars with long rotation periods and high slow-down rates, which indicates an extremely high surface magnetic field ($>10^{14}$ G)[12]. More than 30 magnetars have been discovered so far①. Most of them were discovered by X-ray observations thanks to their wide range of X-ray activity, including short bursts, large outbursts, and giant flares. The quasi-periodic oscillations in the tails of their giant flares and associations with supernova

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① http://www.physics.mcgill.ca/pulsar/magnetar/main.html.

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remnants (SNRs) prove their neutron-star origin[13,14]. X-ray luminosities of magnetars are much larger than their rotational energy loss, and therefore their emission and bursts are widely believed to be powered by large magnetic fields.

Only six magnetars have shown radio pulsations. Their radio pulsations were mostly detected during the decay of X-ray emission[15]. Spectra of these radio emissions are remarkably flat, different from the normal pulsar population whose spectra are steep with negative spectral indices of ~ -1.8[16], except for one magnetar SGR 1745−2900[17]. Bright radio single pulses of magnetars are similar to giant pulses (GPs) of pulsars, with a power-law fluence distribution and shorter duration than the average pulsation profile[18].

SGR J1935+2154 was discovered by Swift-BAT in 2014 through its magnetar-like bursts[19] and cemented by the following Chandra and XMM-Newton observations[20]. Its spin period and time derivative of the period are 3.24 s and 1.43×10^{-11} s s^{-1}, which implies a surface dipolar magnetic field strength of 2.2×10^{14} G, and a characteristic age of about 3.6 kyr. These properties make SGR J1935+2154 a typical Galactic magnetar. Its position strongly suggests an association with a supernova remnant (SNR) G57.2+0.8 at a distance of ~9 kpc[21,22]. Observations of several radio telescopes failed to detect any pulsed or persistent radio emission after the discovery of SGR J1935+2154, and no pulsar wind nebula (PWN) has been found[23-25]. In 2015, 2016 and 2019 this source entered active states and showed burst activities more frequently and intensely[26,27]. Even during the quiescent time, several sporadic XRBs have been detected, which makes it outstanding upon other known magnetars[26].

On April 27, 2020, multiple X-ray bursts were detected from SGR J1935+2154, indicated a new active phase[28]. One day later, FRB 200428 was detected associated with two SGR bursts[6]. After its outburst in April, a number of radio telescopes have undertaken follow-up observations of SGR 1935+2154. Only a few radio bursts were detected[29,30]. X-ray observations showed that the black body temperature and unabsorbed flux in the 0.3−10 keV band of this magnetar have gone through a double exponential decay, and went back to average values three months later[31].

On October 8, 2020, CHIME detected three close bursts with a fluence of 900±160, 9.2±1.6 and 6.4±1.1 Jy ms, respectively[32,33]. A XRB of SGR 1935+2154 was reported by Swift soon after, but was later to be a detector glitch[34]. One day later, during a one-hour observation, FAST detect multiple radio pulses with fluence up to 40 mJy ms[35]. They also detected a periodic signal with a period of 3.24781 s. And single pulses were well aligned in a certain phase of the period.

We have also carried out a follow-up observing campaign using Parkes after the outburst. Here we report the details of this observation and our results. The observation and data reduction are described in Section 2. The results are presented in Section 3 and we discuss the possible implications from our observation in Section 4.

2 Observation and data reduction

During the reactivation of SGR 1935+2154 in October 2020, we carried out a 1.6-hours follow-up observation with the Parkes 64 m radio telescope on October 11, 2020. We used the new ultra-wideband low (UWL) receiver system[36] covering a frequency range of 704−4032 MHz. The full band is split into 26 contiguous sub-bands, each with 128 channels. The channelised signals were recorded with all four polarisations using Parkes Medusa digital systems and 8-bit sampled data with a resolution of 64 μs to be stored in PSRFITS search mode format[37]. As the reported DM of SGR 1935+2154 is around 333 pc cm^{-3}[38], were coherently de-dispersed the data at a DM of 333 pc cm^{-3} within each 1 MHz channel.

We used the pulsar analysis software suite PRESTO① to process the Parkes search mode data. Previous observations show that radio emission from magnetar has very flat spectra[12]. Therefore, the full 3.3 GHz band width data sets were used to search for possible single pulses. We also searched for possible limited band signals using data sub-banded into 704−1200, 1200−1500, 1500−2000, 2000−2500, 2500−3000, 3000−3500, 3500−4032 MHz. We used the routine RFIFIND to identify the strong narrow-band and short-duration broadband radio frequency interference (RFI) and produced RFI mask files. Our pipeline applied a 1.0 s integration time for the RFI identification and a 6σ cutoff to reject time-domain and frequency-domain interference. Our observation was coherently de-dispersed at the reported DM of 333 pc cm^{-3}. We searched DM trials in a range ±10 pc cm^{-3} centered at the reported DM value with a DM step of 0.1 pc cm^{-3}. The PREPDATA routine were then used to de-disperse the data at each of the trial DMs, and remove RFI based on the mask file. Single pulse candidates with a signal-to-noise ratio (S/N) larger than seven were identified using the SINGLE_PULSE_SEARCH.PY routine for each de-dispersed time series file and boxcar filtered with width up to 300 samples was used. All of the several thousands of candidates were grouped using the same method as described in Reference [39]. For these

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① https://github.com/scottransom/presto.

groups, we only visually investigated the candidate with the highest S/N present within that group.

We searched for possible periodic signals using a similar manner to the single pulse searches. Both the full bandwidth and sub-banding data sets were processed. RFI was rejected and marked using RFIFIND and the DM trials are in a range ±10 pc cm^{-3} centered at the 333 pc cm^{-3} with a DM step of 0.1 pc cm^{-3}. As the latest spin period for SGR 1935+2154 in October 2020 was reported by FAST to be 3.24781 s[35], we folded our observation using this period value at each trial DM using the PREPFOLD routine.

3 Results

36 single pulse candidates with S/N≥7 were detected. However, all of them were clearly caused by RFI and no convincing pulse from SGR 1935 + 2154 was detected. We did not detect any convincing candidate from the periodicity-search either.

Limits on the flux density of a radio pulse can be estimated as

$$S_{\mathrm{lim}} = \frac{\sigma \mathrm{S/N}_{\mathrm{min}} T_{\mathrm{sys}}}{G\sqrt{\Delta v N_p t_{\mathrm{obs}}}} \qquad (1)$$

where a system temperature of $T_{\mathrm{sys}} = 22$ K, a loss factor $\sigma = 1.5$ and telescope antenna gain $G = 1.8$ for UWL receiver of Parkes telescope were used[36]. Assuming a pulse width of 0.5 ms and flat spectrum, our non-detection of signal with S/N above 7 put a fluence limitation of 35 mJy ms for the full 3.3 GHz bandwidth data sets. The limits of flux density and fluence of our single pulse search at different frequencies ranges are presented in Table 1.

As for periodic signals, Equation (1) should time $\sqrt{\frac{\delta}{1-\delta}}$ and δ is the duty cycle. According to MNC detection[40], we assume a pulse width of 100 ms, corresponding to a duty cycle of 0.03. Our non-detection with the 1.6-hours observation of the full 3.3 GHz band width put a 7σ limit of 3.6 μJy. Limits of flux density and fluence of our periodicity search at different frequencies ranges are presented in Table 1.

Table 1. Summary of the flux density and fluence limits of the single pulses and periodicity search of SGR 1935+2154 with Parkes UWL receiver.

Freq. range (MHz)	Assuming width single pulse(ms)	Assuming width periodic signal(ms)	single pulse/periodic signal (Flux density limit (7σ))	single pulse/periodic signal (Fluence limit (7σ))
704-1200	0.5	100	181 mJy/9.2 μJy	91 mJy ms/0.92 mJy ms
1200-1500	0.5	100	234 mJy/11.9 μJy	117 mJy ms/1.19 mJy ms
1500-2000	0.5	100	181 mJy/9.2 μJy	91 mJy ms/0.92 mJy ms
2000-2500	0.5	100	181 mJy/9.2 μJy	91 mJy ms/0.92 mJy ms
2500-3000	0.5	100	181 mJy/9.2 μJy	91 mJy ms/0.92 mJy ms
3000-3500	0.5	100	181 mJy/9.2 μJy	91 mJy ms/0.92 mJy ms
3500-4032	0.5	100	181 mJy/9.2 μJy	91 mJy ms/0.92 mJy ms
704-4032	0.5	100	70 mJy/3.6 μJy	35 mJy ms/0.36 mJy ms

4 Discussion

Our search of periodic signal and single pulses from SGR 1935+2154 with Parkes UWL receiver did not find any convincing signal. An integration of 1.6-hours observation allows us to derive 7σ upper bounds on the fluence of 0.36 and 35 mJy ms for the single pulse and periodicity search using the full 3.3 GHz bandwidth, respectively. The single pulse fluence limit is slightly larger than the result of Reference [41] on April 2020 (i.e. 25 mJy ms) and we noticed that Zhu et al.[35] carried out a one-hour observation of SGR 1935+2154 using FAST radio telescope just two days before our campaign. The brightest single pulse detected by them has a fluence up to 40 mJy ms, which is well above our fluence limit of the whole 3.3 GHz band data sets, but below our limits using a bandwidth of 500 MHz. Our results suggest that either the burst event rate of SGR 1935 is reduced, or more likely, the spectrum of SGR 1935 is not flat, or its single pulses are intrinsically narrow-band.

Our limit on the flux density of periodical signals using the full 3.3 GHz bandwidth data sets is 3.6 μJy, much lower than MNC's periodical detection of the flux density of 4 mJy on May 30, 2020[40] and CHIME's limit of 0.2 mJy on May 30, 2020[42], and slightly lower than the Green Bank Telescope's limitation of 6.3 μJy on October 16, 2020[43]. Zhu et al.[35] also claimed detection of periodic radio emission, however, no exact flux density or fluence measurement was presented. It is notable that the CHIME's limit of 0.2 mJy was only 9 hours after the MNC's detection of 4 mJy, which indicates a sharp of flux density of the periodic radio radiation. If the flux density of FAST detection is larger than our limit, this could be the second time that this phenomenon has been detected on SGR 1935+2154, which is similar to the intermittent pulsation behavior. One of the six radio-loud magnetars J1810-197 had shown intermittent pulsation behavior[44]. This source shut down radio pulsation in 2008 after an on-state lasting 32 months. It decreased during the first 10 months but been steady for the rest of the on-period and suddenly wend off without any secular decrease.

However, if the flux density of FAST detection is much smaller than our limit, then it will show that magnetars could have periodic radiation with flux density that spans several orders of magnitude. The so-called "shut down" state of magnetars like J1810-197 could also be detected with weak emission in more sensitive observation. Our limit of the periodic signal could derive that only telescopes with a diameter larger than 139 m have a chance to make a 10σ detection with one-hour observation with a bandwidth of 300 Mhz. Telescopes with high sensitivity like FAST are necessary to uncover the radio activities for magnetars like SGR 1935+2154.

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Conflict of interest

The authors declare no conflict of interest.

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WU Xuefeng (corresponding author) is a Research Professor and the chief scientist of the High Energy Time-Domain Astronomy Group of PMO. He received his PhD degree from Nanjing University in June 2005. He is a theoretical astrophysicist in high energy astrophysics, time-domain astronomy and cosmology. His main concerns are (magneto-) hydrodynamic (relativistic or non-relativistic shock waves, accretion and outflow) and radiation processes in these spectacular phenomena, and the physical nature of the remnants (compact objects, such as black holes, neutron stars, and white dwarfs). He is also interested in using astronomical data to probe the Universe as well as to test fundamental physics.

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利用 Parkes 望远镜超宽带低频接收机搜寻 SGR 1935+2154 的射电脉冲

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摘要: 在快速射电暴(FRB)被发现后不久磁陀星就被提出是可能的起源. 从 SGR 1935+2154 中探测到的第一个河内快速射电暴 FRB 200428,使得这一设想更令人信服. 在 2020 年 10 月,这个源再次进入活跃状态. 我们使用 Parkes 64 m 射电望远镜的新型超宽带低频段(UWL)接收机,对 SGR 1935+2154 进行了 1.6 h 的后随观测,频率范围为 704-4032 MHz. 在我们的单脉冲和周期性搜索中没有搜寻到令人信服的信号. 我们使用完整的 3.3 GHz 带宽数据集获得的周期信号通量密度限制为 3.6 μJy,这是对 SGR 1935+2154 最严格的限制. 我们对单脉冲通量的全带宽限制为 35 mJyms,低于 FAST 射电望远镜在我们观测的两天前探测到的最亮的单脉冲. 假设 SGR 1935+2154 在观察过程中是活跃的,我们的结果表明,它的射电暴发要么是窄带的,要么呈现较陡的频谱.

关键词: 磁陀星;快速射电暴;软伽玛射线复现源