Searching for radio pulsation from SGR 1935+2154 with the Parkes Ultra-Wideband Low receiver

Zhenfan Tang,1,2 Songbo Zhang,1 * Shi Dai,3 Ye Li,1 Xuefeng Wu1 *
1Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China
2School of Astronomy and Space Sciences, University of Science and Technology of China, Hefei 230026, China
3Western Sydney University, Locked Bag 1797, Penrith South DC, NSW 1797, Australia

ABSTRACT
Magnetars have been proposed to be the origin of FRBs soon after its initial discovery. The detection of the first Galactic FRB 20200428 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 35mJy ms, which is well below the brightest single pulses detected by the FAST radio telescope just two before our observation. Assuming that SGR 1935+2154 is active during our observation, our results suggest that its radio bursts are either intrinsically narrowband or show a steep spectrum.

Key words: stars: magnetars - fast radio bursts.

1 INTRODUCTION

Fast radio bursts are one of the most energetic sources in the universe with luminosities up to 1039 erg s−1. Since the original discovery in 2007 (Lorimer et al. 2007), 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 (Chatterjee et al. 2017; Collaboration et al. 2020b). 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 (The CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020). Considering the dispersion delay, the two X-ray components of the magnetar burst occur within 3 ms of the radio burst components (Zhang et al. 2020b).

Magnetars have been proposed to be the origin of FRBs (Popov & Postnov 2007) soon after its initial discovery. A large number of papers discussed this model from different perspectives (Lyubarsky 2014; Katz 2016). 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 (Gajjar et al. 2018)) 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 (Zhang 2020). 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 (> 10¹⁴ G) (Kaspi & Beloborodov 2017). More than 30 magnetars have been discovered so far. Most of them were discovered by X-ray observations thanks to their widespread 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 remnants prove their neutron-star origin (Mazets et al. 1979; Cline et al. 1982). 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 (Camilo et al. 2007). 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 (Maron et al. 2000), except for one magnetar SGR 1745−2900 (Pennucci et al. 2015). Bright radio single pulses of magnetars are similar to giant pulses(GPs) of pulsars, with a power-law fluence distribution and shorter duration than average pulsation profile (Esposito et al. 2020).

SGR J1935+2154 was discovered by Swift-BAT in 2014 through its magnetar-like bursts (Stamatikos et al. 2014) and cemented by the following Chandra and XMM-Newton observations (Israel et al. 2016). Its spin period and time derivative of the period are 3.24 s

* Corresponding author. E-mail: sbzhang@pmo.ac.cn; xfwu@pmo.ac.cn

1 http://www.physics.mcgill.ca/ pulsar/magnetar/main.html
and $1.43 \times 10^{-11}$ s$^{-1}$, which implies a surface dipolar magnetic field strength of $2.2 \times 10^{14}$ G, and a characteristic age of about 3.6 kyr. These properties make SGR J1935+2154 a typical Galactic magnetar. Its position strongly suggesting an association with a supernova remnant (SNR) G57.2+0.8 at a distance of ~ 9kpc. (Gaensler 2014; Zhou et al. 2020) 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 (PWNe) has been found (Fong & Berger 2014; Surnis et al. 2014; Burgay et al. 2014).

In 2015, 2016 and 2019 this source entered active state and during burst activities more frequently and intensely (Younes et al. 2017; Lin et al. 2020). Even during the quiescent time, several sporadic XRBs have been detected, which makes it outstanding upon other known magnetars (Younes et al. 2017).

On April 27, 2020, multiple X-ray bursts were detected from SGR J1935+2154, indicated a new active phase (Barthelmy et al. 2020). One day later, FRB 200428 was detected associated with two SGR bursts (Zhang et al. 2020b). After its outburst in April, a number of radio telescopes have undertaken follow-up observations of SGR J1935+2154. Only a few radio bursts were detected (Zhang et al. 2020c; Kirsten et al. 2021). 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 (Younes et al. 2020).

On October 8, 2020, CHIME detected three close bursts with fluence of $900 \pm 160$, $9.2 \pm 1.6$ and $6.4 \pm 1$ mJy ms, respectively (Good & Chime/FRB Collaboration 2020; Pleunis & CHIME/FRB Collaboration 2020). A XRB of SGR J1935+2154 was reported by Swift soon after, but was later to be a detector glitch (Tohuavavohu 2020). One day later, during a one-hour observation, FAST detect multiple radio pulses with fluence up to 40 mJy ms (Zhu et al. 2020). They also detected a periodic signal with a period of 3.24781 s. And single pulse were well aligned in a certain phase of the period.

We have also carried out a follow-up observing campaigns 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 J1935+2154 in October 2020, we carried out an 1.6hr follow-up observation with the Parkes 64 m radio telescope on October 11, 2020. We used the new ultra-wideband low (UWL) receiver system (Hobbs et al. 2020) 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 (Hotan et al. 2004). As the reported DM of SGR J1935+2154 is around 333 pc cm$^{-3}$ (Collaboration et al. 2020a), we 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 PRESTO 2 to process the Parkes search mode data. Previous observations show that radio emission from magnetar have very flat spectra. (Kaspi & Beloborodov 2017). 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 RFFIND to identify strong narrow-band and short-duration broadband radio frequency interference (RFI) and produced RFI mask files. Our pipeline applied a 1.0s 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 PREFPDATA 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 filtering with width up to 300 samples was used. All of the several thousands of candidates were grouped using the same method as described in Zhang et al. (2020a). For these 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 RFFIND 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 J1935+2154 in 2020 October was reported by FAST to be 3.24781s (Zhu et al. 2020), we folded our observation using this period value at each trial DM using 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 J1935+2154 was detected. We also did not detect any convincing candidate from the periodicity-search.

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

$$S_{\text{lim}} = \frac{\sigma S}{N_{\text{min}} g} T_{\text{sys}} \sqrt{\Delta f N_{\text{probs}}},$$

where a system temperature of $T_{\text{sys}} = 22$ K, a loss factor $\sigma = 1.5$ and telescope antenna gain $g = 1.8$ for UWL receiver of Parkes telescope were used. (Hobbs et al. 2020). 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 times $\sqrt{\frac{2}{c \delta}}$ and $\delta$ is the duty cycle. According to MNC detection (Burgay et al. 2020), we assume a pulse width of 100ms, corresponding to a duty cycle of 0.03. Our non-detection with the 1.6h observation of the full 3.3GHz band width put a 7σ limit of 3.6μJy. Limits of flux density and fluence of our periodicity search at different frequencies ranges are presented in Table 1.

4 DISCUSSION

Our search of periodic signal and single pulses from SGR J1935+2154 with Parkes UWL receiver did not find any convincing signal. An integration of 1.6h observation allows us to derive 7σ upper bounds on the fluence of 0.36 mJy ms and 35 mJy ms for the single pulse

---

2 https://github.com/scottransom/presto
and periodicity search using the full 3.3 GHz bandwidth, respectively. The single pulse fluence limit is slightly larger than the result of Bailes et al. (2021) on April 2020 (i.e. 25 mJy ms) and we noticed that Zhu et al. (2020) have 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 SGR1935 is reduced, or more likely, the spectrum of SGR1935 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 $\mu$Jy, much lower than MNC’s periodical detection of flux density of 4 mJy on May 30 2020 (Burgay et al. 2020) and CHIME’s limit of 0.2 mJy on May 30, 2020 (Tan & Chime/Pulsar Collaboration 2020), and slightly lower than the Green bank telescope’s limitation of 6.3 mJy on October 16, 2020 (Straal et al. 2020). Zhu et al. (2020) 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 flux of high 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 (Camilo et al. 2016). This source shut down radio pulsation in 2008 after a on state lasting 32 months. It decreasing during the first 10 months but been steady for rest of the on period and suddenly went 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 chance to make a 10 $\sigma$ detection with one-hour observation with bandwidth of 300 MHz. Telescopes with high sensitivity like FAST are necessary to uncovering the radio activities for Magnetars like SGR 1935+2154.

### ACKNOWLEDGEMENTS

The Parkes radio telescope (“Murriyang”) is part of the Australia Telescope National Facility which is funded by the Australian Government for operation as a National Facility managed by CSIRO. This paper includes archived data obtained through the CSIRO Data Access Portal (https://data.csiro.au). This work was supported by ACAMAR Postdoctoral Fellow, the National Natural Science Foundation of China (Grant No. 11725314, 12041306, 11903019), China Postdoctoral Science Foundation (Grant No. 2020M681758).

### REFERENCES

Bailes M., et al., 2021, Monthly Notices of the Royal Astronomical Society, 503, 5367
Barthelmy S. D., et al., 2020, GRB Coordinates Network, 27657, 1
Bochenek C. D., Ravi V., Belov K. V., Hallinan G., Kocz J., Kulkarni S. R., McKenna D. L., 2020, Nature, 587, 59
Burgay M., Israel G. L., Rea N., Possenti A., Coti Zelati F., Esposito P., Mereghetti S., Tiengo A., 2014, The Astronomer’s Telegram, 6371, 1
Burgay M., et al., 2020, The Astronomer’s Telegram, 13783, 1
Camilo F., et al., 2007, The Astrophysical Journal, 669, 561
Camilo F., et al., 2016, The Astrophysical Journal, 820, 110
Chatterjee S., et al., 2017, Nature, 541, 58
Cline T. L., et al., 1982, ApJ, 255, L45
Collaboration T. C., et al., 2020a, arXiv:2005.10324 [astro-ph]
Collaboration T. C., et al., 2020b, Nature, 582, 351
Esposito P., et al., 2020, arXiv:2004.04083 [astro-ph] 10.3847/2041-8213/ab9742
Fong W., Berger E., 2014, GRB Coordinates Network, 16542, 1
Gaensler B. M., 2014, GRB Coordinates Network, 16533, 1
Gajjar V., et al., 2018, The Astrophysical Journal, 863, 2
Good D., Chime/Frb Collaboration 2020, The Astronomer’s Telegram, 14074, 1
Hobbs G., et al., 2020, Publications of the Astronomical Society of Australia, p. 16
Hotan A. W., van Straten W., Manchester R. N., 2004, arXiv:astro-ph/0404549
Israel G. L., et al., 2016, Monthly Notices of the Royal Astronomical Society, 457, 3448
Kaspi V. M., Beloborodov A., 2017, Annual Review of Astronomy and Astrophysics, 55, 261
Katz J. I., 2016, The Astrophysical Journal, 826, 226
Kirsten F., Snellers M. P., Jenkins M., Nimmo K., van den Eijnden J., Hessels J. W. T., G aworoski M. P., Yang J., 2021, Nature Astronomy, 5, 414
Lin L., Gogus E., Roberts O. J., Baring M. G., Kouveliotou C., Kaneko Y., van der Horst A. J., Youngs G., 2020, The Astrophysical Journal, 902, L43
Lorimer D. R., Bailes M., McLaughlin M. A., Narkevic D. J., Crawford F., 2007, Science, 318, 777
Lyubarsky Y., 2014, MNRAS, 442, L9
Maron O., Kijak J., Kramer M., Wielebinski R., 2000, Astronomy and Astrophysics Supplement Series, 147, 195
Mazets E., Golentskii S., Il’inskii V., Guryan Y. A., et. al., 1979, Nature, 282, 587
Pennucci T. T., et al., 2015, The Astrophysical Journal, 808, 81

| Freq. Range (MHz) | Assuming Width Single Pulse(ms) | Assuming Width Periodic Signal(ms) | Flux Density Limit ($\sigma$) Single Pulse/Periodic Signal | Fluence Limit ($\sigma$) Single Pulse/Periodic Signal |
|------------------|---------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|
| 704 – 1200       | 0.5                             | 100                               | 181 mJy / 9.2 $\mu$Jy                          | 91 mJy ms / 0.92 mJy ms                        |
| 1200 – 1500      | 0.5                             | 100                               | 234 mJy / 11.9 $\mu$Jy                         | 117 mJy ms / 1.19 mJy ms                      |
| 1500 – 2000      | 0.5                             | 100                               | 181 mJy / 9.2 $\mu$Jy                          | 91 mJy ms / 0.92 mJy ms                      |
| 2000 – 2500      | 0.5                             | 100                               | 181 mJy / 9.2 $\mu$Jy                          | 91 mJy ms / 0.92 mJy ms                      |
| 2500 – 3000      | 0.5                             | 100                               | 181 mJy / 9.2 $\mu$Jy                          | 91 mJy ms / 0.92 mJy ms                      |
| 3000 – 3500      | 0.5                             | 100                               | 181 mJy / 9.2 $\mu$Jy                          | 91 mJy ms / 0.92 mJy ms                      |
| 3500 – 4032      | 0.5                             | 100                               | 181 mJy / 9.2 $\mu$Jy                          | 91 mJy ms / 0.92 mJy ms                      |
| 704 – 4032       | 0.5                             | 100                               | 70 mJy / 3.6 $\mu$Jy                           | 35 mJy ms / 0.36 mJy ms                      |
Zhenfan Tang et al.

Pleunis Z., CHIME/FRB Collaboration 2020, The Astronomer’s Telegram, 14080, 1
Popov S. B., Postnov K. A., 2007, arXiv:0710.2006 [astro-ph]
Stamatikos M., Malesani D., Page K. L., Sakamoto T., 2014, GRB Coordinates Network, 16520, 1
Straal S., Maan Y., Gelfand J., van Leeuwen J., Kouveliotou C., 2020, The Astronomer’s Telegram, 14151, 1
Surnis M. P., Krishnakumar M. A., Maan Y., Joshi B. C., Manoharan P. K., 2014, The Astronomer’s Telegram, 6376, 1
Tan C. M., Chime/Pulsar Collaboration 2020, The Astronomer’s Telegram, 13838, 1
The CHIME/FRB Collaboration et al., 2020, Nature, 587, 54
Tohuwavohu A., 2020, The Astronomer’s Telegram, 14076, 1
Younes G., et al., 2017, ApJ, 847, 85
Younes G., et al., 2020, The Astrophysical Journal, 904, L21
Zhang B., 2020, Nature, 587, 45
Zhang S.-B., et al., 2020a, The Astrophysical Journal Supplement Series, 249, 14
Zhang S. N., et al., 2020b, The Astronomer's Telegram, 13696, 1
Zhang C. F., et al., 2020c, The Astronomer’s Telegram, 13699, 1
Zhou P., Zhou X., Chen Y., Wang J.-S., Vink J., Wang Y., 2020, The Astrophysical Journal, 905, 99
Zhu W., et al., 2020, The Astronomer’s Telegram, 14084, 1