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# Discovery of an extremely intermittent periodic radio source

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## ABSTRACT

We report the serendipitous discovery of an extremely intermittent radio pulsar, PSR J1710–3452, with a relatively long spin period of 10.4 s. The object was discovered through the detection of 97 bright radio pulses in only one out of 66 epochs of observations spanning almost three years. The bright pulses have allowed the source to be localized to a precision of 0.5 arcsec through radio imaging. We observed the source location with the *Swift* X-ray telescope but did not detect any significant X-ray emission. We did not identify any high-energy bursts or multifrequency counterparts for this object. The solitary epoch of detection hinders the calculation of the surface magnetic field strength, but the long period and the microstructure in the single-pulses resembles the emission of radio-loud magnetars. If this is indeed a magnetar, it is located at a relatively high Galactic latitude ( $2.9^\circ$ ), making it potentially one of the oldest and the most intermittent magnetars known in the Galaxy. The very short activity window of this object is unique and may point towards a yet undetected population of long period, highly transient radio emitting neutron stars.

**Key words:** techniques: interferometric – stars: magnetars – stars: neutron – radio continuum: transients.

## 1 INTRODUCTION

Magnetars are neutron stars with high surface magnetic field strengths of the order of  $10^{14}$  G (with some exceptions), and periods ranging between 2 and 12 s. Most are bright and persistent X-ray emitters with luminosities exceeding the spin-down energy. Sometimes, they exhibit luminous high-energy bursts, accompanied by erratic rotational behaviour, unlike their rotation-powered canonical neutron star cousins (see Kaspi & Beloborodov 2017, for a review). This high-energy emission is believed to be powered by the decay of the ultra-strong magnetic field (Duncan & Thompson 1992) as the energy required for the emission is much larger than what is available from the inferred spin-down luminosity of the neutron star. Only 6 out of 26 known magnetars have shown radio emission so

far (McGill magnetar catalogue; Olausen & Kaspi 2014), which is usually observed after a high-energy outburst and fades away at later times. Given this small sample of radio-loud magnetars, the origin and mechanism of their emission is not well-understood. The radio emission from the radio-loud magnetars (see for instance, cases of XTE J1810–197 and *Swift* J1818.0–1607) is also highly transient in nature. It starts and stops abruptly and shows rapid variability in pulse profile shape, flux density, and spectral index (see Camilo et al. 2016; Maan et al. 2019; Champion et al. 2020; Esposito et al. 2020; Caleb et al. 2022a, and references therein).

Unlike magnetars, the majority of pulsars are observed as persistent periodic radio emitters. However, their radio emission shows variability over a wide range of time-scales ranging from nulling, which is the cessation of emission over a few rotation periods (Wang, Manchester & Johnston 2007) to the months to years-long disappearance of emission in intermittent pulsars (Kramer et al. 2006; Camilo et al. 2012; Lorimer et al. 2012; Lyne et al.

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2017). There are a few neutron stars that show transient emission paired with magnetar-like bursts, such as PSR J1119–6127 and PSR J1622–4950. PSR J1119–6127 is a high magnetic field pulsar that has emitted magnetar-like bursts followed by soft X-ray flares (Göğüş et al. 2016). On the other hand, PSR J1622–4950 was discovered through its pulsed radio emission and was classified as a magnetar on account of its emission at X-rays and inferred magnetic field strength. Unlike the rest of the radio-loud magnetars, for PSR J1622–4950, no known high-energy burst was detected before the radio emission is believed to have started (Levin et al. 2010).

Luminous, transient radio emission from radio-loud magnetars is also of interest because of the similarities to the enigmatic Fast Radio Bursts (FRBs): microsecond to millisecond duration radio flashes that are cosmological in nature (e.g. Caleb & Keane 2021; Petroff, Hessels & Lorimer 2022). Recently, a Galactic magnetar, SGR J1935+2154, emitted bright radio bursts following increased high-energy activity. One of these bursts approached the luminosity of FRBs, suggesting, perhaps a connection between magnetars and FRB progenitors (Bochenek et al. 2020; The CHIME/FRB Collaboration 2020). Transient radio emission from known and newly discovered magnetars might be the key in understanding the potential connection between FRBs and magnetars.

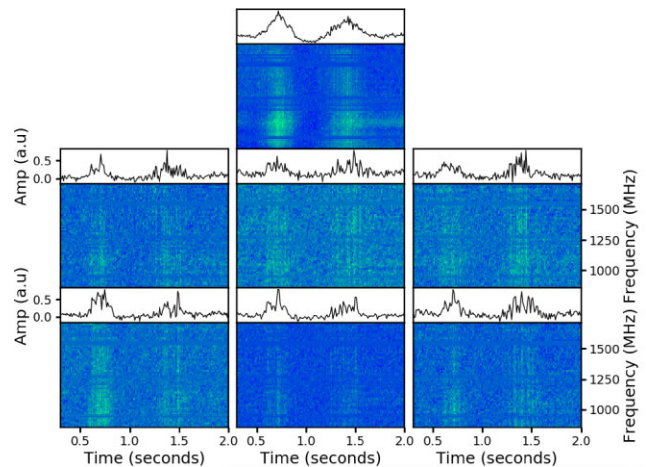
Here, we report the discovery of an extremely transient radio emitting neutron star (RENS), PSR J1710–3452. This object shows characteristics similar to radio-loud magnetars and presents an intriguing example of a long-period pulsar that straddles the boundary between regular and transient RENS. In this paper, we describe the discovery and multiwavelength counterpart search in Section 2. The results of single-pulse analysis are described in Section 3 and the implications of our results are discussed in Section 4. Finally, we conclude our findings in Section 5.

## 2 OBSERVATIONS

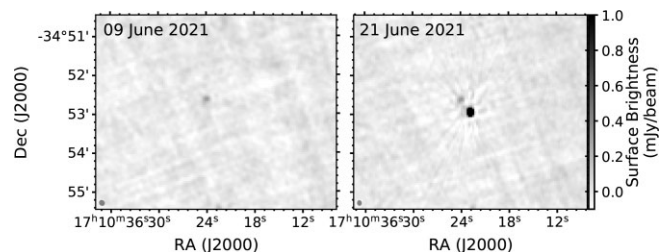
### 2.1 Discovery and localization

PSR J1710–3452 was serendipitously discovered through its single-pulses on 2021 June 21 during an observation of the millisecond pulsar (MSP), PSR J1708–3506 with the *MeerKAT* telescope (Jonas & MeerKAT Team 2016), as part of the MeerTIME programme (Bailes et al. 2020). The single-pulses were detected through the Meer (more) TRansients and Pulsars (MeerTRAP) pipeline which is a realtime commensal mode back end on the *MeerKAT* telescope (Rajwade et al. 2022). The observation lasted 21 min and resulted in the detection of 97 pulses (see Fig. 1 for example) from the object with a dispersion measure (DM) of  $189 \pm 0.5$  pc cm<sup>-3</sup>. A simple periodicity search resulted in the clear detection of a period of 10.4 s between the radio pulses. The pulses were detected in the incoherent beam with a total field of view of  $\sim 1.3^{\circ 2}$  and hence, the localization of the new source was poor. A search for known sources within the incoherent beam revealed the bright 0.7 s pulsar, PSR J1708-3426 with a similar DM ( $190 \pm 2$  pc cm<sup>-3</sup>). While the DM of PSR J1708-3426 was within the  $1\sigma$  uncertainty range of the DM of PSR J1710–3452, the measured period was not harmonically related to the period of PSR J1708-3426, leading us to believe that PSR J1710–3452 was a new object.

The only way to conclusively prove PSR J1710–3452 as a newly discovered object was to localize it in the radio images. The signal-to-noise ratio (S/N) of the single-pulses from PSR J1710–3452 was high enough for it to be detected in the synthesis radio images made from the visibilities recorded simultaneously. The minimum integration time of 8 s for the visibilities compared to the rotation period of 10.4 s resulted in some integrations without any pulsed



**Figure 1.** A gallery of some of the single radio pulses from PSR J1710–3452 along with the average radio pulse profile (top-most plot). For each pulse, the top panel shows intensity versus time and the bottom panel shows the dedispersed dynamic spectrum. This plot shows the diversity in the emission showing sub-structure and quasi-periodic sub-pulses. Here, a.u. stands for arbitrary units.



**Figure 2.** *MeerKAT* images of the position of PSR J1710–3452 on 2021 June 9 (left) and 2021 June 21 (right). The synthesized beam is shown as a grey circle in the bottom-left corner of each panel. PSR J1710–3452 can be clearly seen in the right-hand image.

emission. Using the known period and the time-domain data, we made single ‘ON’ and ‘OFF’ pulse images by adding an equal number of ‘ON’ and ‘OFF’ pulse integrations. Subtracting the two images resulted in the detection of the source at the sky location RA  $17^{\text{h}}10^{\text{m}}22^{\text{s}}.81(3)$ , Dec.  $-34^{\circ}52'57''.5(5)$ . This position also confirmed that it was not associated with PSR J1708-3426, which is located more than 33 arcmin away.

Using an image made from the entire 21 min observation (right-hand panel of Fig. 2), we determined a flux density for the continuum source at the position of PSR J1710–3452 of  $12.5 \pm 1.3$  mJy at 1283.6 MHz.<sup>1</sup> As the nearby MSP PSR J1708–3506 is part of the monitoring campaign led by the MeerTIME project (Bailes et al. 2020), the field is being observed regularly with a cadence of roughly two weeks. At the time of writing this paper, this field had been observed for a total of 66 epochs, totalling 1320 min of observing time. Although no previous detections of bright single-pulses had been made by MeerTRAP, we investigated whether the source might have been present previously, but either fainter, or emitting in a different mode. We imaged the *MeerKAT* interferometric data from a total of 19 epochs between 2021 June 9 and 2022 July 13. All the

<sup>1</sup>The beam correction is approximate for the MTMFS algorithm, so we have put a 10 per cent uncertainty to be conservative.

radio images except the discovery epoch resulted in non-detection of the object with the median and the most stringent  $3\sigma$  upper limits on the flux density being 81 and 51  $\mu\text{Jy}$ , respectively (see Fig. 2 for an example). This puts the flux density ratio between the ‘ON’ and ‘OFF’ states to be greater than 240 for the most stringent limit. Since there was a direct correlation between non-detections in time domain and radio images, we were confident that if no pulses were detected by the MeerTRAP back-end then the source was not emitting radio pulses. We searched through archival radio images from different telescopes to check if the continuum source was detected elsewhere. These included the TIFR GMRT Sky Survey (TGSS; Intema et al. 2017) at 147.5 MHz, the Rapid ASKAP Continuum Survey (RACS; McConnell et al. 2020) at 887.5 MHz, and the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) at 1400 MHz. We did not detect the continuum source in any of the radio images with  $3\sigma$  flux density upper limits of 60, 1.2, and 1.95 mJy at 147.5, 887.5, and 1400 MHz, respectively. These survey observations encompass the duration of almost 26 yr starting with the NVSS observation which was carried out on 1995 January 17.<sup>2</sup>

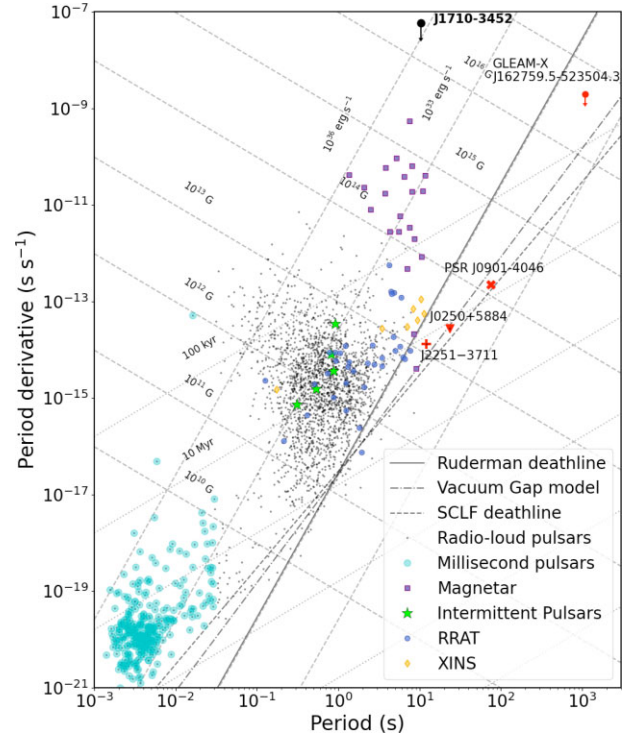
## 2.2 Multiwavelength counterpart

In order to check if the detection of radio pulses was associated with the onset of any high-energy emission, we looked for realtime triggers from three all-sky burst monitors: *Swift-BAT*, *Fermi-GBM*, and *INTEGRAL* (Winkler et al. 2003; Meegan et al. 2009; Krimm et al. 2013). We searched for triggers issued by the respective burst report systems from the direction of PSR J1710–3452 for up to two weeks prior to the detection of radio pulses. Along with reported bursts, we also checked for sub-threshold bursts in *GBM*, i.e. bursts that are just below the detection threshold of the instrument (see Younes et al. 2020, for more details). No confirmed bursts were found in this search although a few sub-threshold burst candidates that were nominally located towards PSR J1710–3452 were found in the *Fermi-GBM* data. For these bursts, the localization error was too large to confirm any association. We also searched for archival data on this field in observations with the *Swift-XRT*, *XMM-Newton*, and *Chandra* X-ray telescopes, but unfortunately none of these telescopes have observed this field. Consequently, we carried-out target of opportunity observations with the *Swift-XRT* telescope for a total of 2.5 ks in the photon counting mode. We did not detect an X-ray source at the location of PSR J1710–3452 and place a  $3\sigma$  upper limit on the absorbed X-ray flux of  $4.3 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ . The measured limit is not very constraining for emission models and deeper X-ray observations with more sensitive telescopes like *XMM-Newton* or *Chandra* are needed to reveal if PSR J1710–3452 is an X-ray emitter.

We also checked the position of PSR J1710–3452 in all the archival optical surveys, namely the Digitized Sky Survey (DSS)<sup>3</sup> and the Dark energy CAmera Plane Survey (DeCAPS; Schlafly et al. 2018). We did not detect any optical source at the location of PSR J1710–3452. While we see a hint of emission in the *z*-band image from DeCAPS, it is not significant ( $\sim 1.5$ – $2\sigma$ ) enough to warrant further investigation. From the non-detections, we calculate  $5\sigma$  upper limits of 23.5, 22.6, 22.1, 21.6, and 20.3 magnitude in the *grizY* bands from Saydjari et al. (2022). We also looked for an infrared counterpart in the 2-Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and

<sup>2</sup>Exact dates were not available for the TGSS (between 2010 and 2012) and RACS (between 2019 and 2021) observations.

<sup>3</sup>[http://gss.stsci.edu/zzzOldWebSite/DSS/dss\\_home.htm](http://gss.stsci.edu/zzzOldWebSite/DSS/dss_home.htm)



**Figure 3.** Period–Period derivative plot showing the known pulsar population (ATNF pulsar catalogue version 1.69). In particular, we highlight the XINS, magnetars, and rotating radio transients (RRATs). The large black circle with an upper limit arrow shows the best constrained position of PSR J1710–3452 in the diagram. Various representative pulsar death-lines from different theoretical models are also shown.

did not find any. The  $10\sigma$  upper limits on the infrared magnitudes in the *J*, *H*, and *K<sub>s</sub>* bands are 15.8, 15.1, and 14.3, respectively.

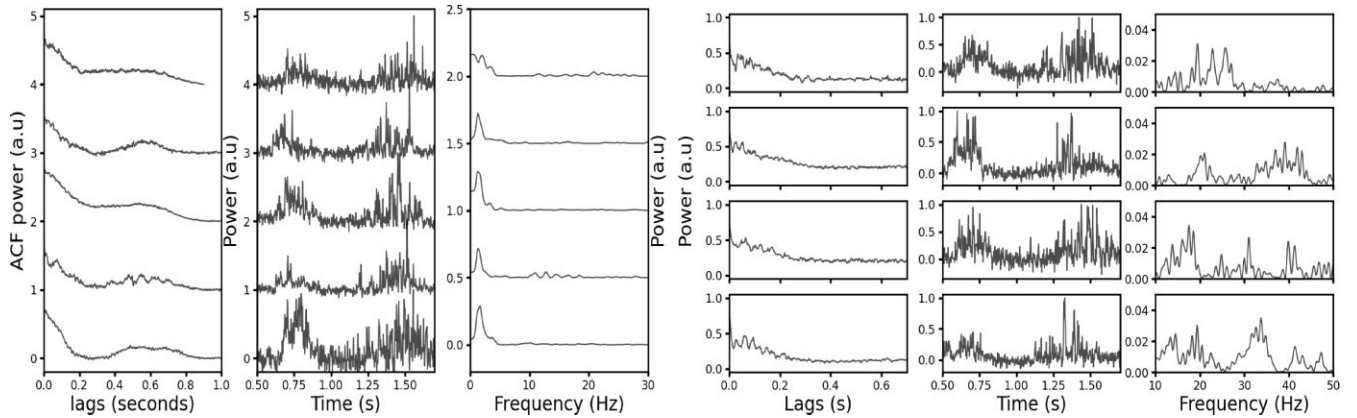
## 3 RESULTS

### 3.1 Timing

We undertook a timing analysis using the single-pulses and derived a rotation period of 10.412(1) s. Our single-epoch detection allowed us to only obtain an upper limit of  $5.9 \times 10^{-8} \text{ ss}^{-1}$  for the period-derivative, which corresponds to an upper limit of  $2.5 \times 10^{16} \text{ G}$  on the surface magnetic field strength. This places PSR J1710–3452 in the region of the *P* –  $\dot{P}$  diagram that is occupied by magnetars and high magnetic field pulsars (see Fig. 3) or close to the X-ray isolated neutron stars (XINS) or below the pulsar death lines if we assume that PSR J1710–3452 comes from an older population of magnetars (see Section 4.3).

### 3.2 Pulse shape and microstructure

The single-pulses show broadly similar emission but there is a large diversity of structure on a smaller time-scale. Every single-pulse shows two main emission components; each comprising several narrow, broad-band, and in some instances, quasi-periodic sub-pulses (see Fig. 4 for example). The two main components are separated by approximately 0.7 s with a total pulse width spanning more than 1 s, corresponding to a pulsed duty cycle of  $\sim 10$  per cent. This large duty cycle does not follow the typical duty-cycle-period anticorrelation seen in RENS (Johnston & Karastergiou 2019)



**Figure 4.** *Left:* Examples of single-pulses from PSR J1710–3452 showing the sub-pulse structure (middle) with the ACF (left) and the Lomb–Scargle periodogram (right). *Right:* Four examples of single-pulses showing quasi-periodic structure (middle) with the ACF of the trailing component (left) and the corresponding Lomb–Scargle periodogram (right). Here, a.u. stands for arbitrary units.

and is closer to what is observed in radio-loud magnetars (Caleb et al. 2022a). To quantify the narrow substructure, we computed the autocorrelation function (ACF) for each single-pulse. For total intensity at each sample,  $I_t$ , the ACF is given by

$$\text{ACF}(\Delta t) = \frac{\sum_i (I(t))(I(t + \Delta t))}{\sqrt{\sum_i (I(t))^2 \sum_i (I(t + \Delta t))^2}}, \quad (1)$$

where  $I(t + \Delta t)$  is the intensity of the sample at a delay of  $\Delta t$ . We computed the ACF for a range of  $\Delta t$  in order to see any systematic structure of the single-pulses. For pulses where quasi-periodic microstructure was clearly visible, we measured the distance between the minima and maxima of the different peaks (see right-hand panel of Fig. 4). These measurements lie in the range 0.03–0.06 s. For each single-pulse, we also computed the Lomb–Scargle periodogram (Scargle 1982) in order to study the quasi-periodicity between the sub-bursts.

The result of this analysis for five sample pulses is shown in Fig. 4. The periodogram is dominated by the 1.35 Hz periodicity which corresponds to the separation between the two main components. However, we find quasi-periodic signals in the trailing component of the radio profile for a few single-pulses.

## 4 DISCUSSION

### 4.1 Transient nature of the radio emission

Radio emission from the known sample of RENS shows a lot of diversity. One of its extreme manifestations is intermittency. Following a period of radio silence, known intermittent RENS show regular emission over a time span of months in their active window (Camilo et al. 2012; Lorimer et al. 2012; Lyne et al. 2017). However, there are a few exceptional examples. PSR J1832+0029 was only detected once in a 10 min observation in its ‘OFF’ state (Wang et al. 2020), while PSR J1841–0500 has exhibited nulls over a long-duration when it was in its ‘ON’ state (Camilo et al. 2012). Given that the spin-down rate of these pulsars remained unchanged during these brief emission/nulling episodes, these were possibly one-off events. PSR J1929+1357 provides a much more interesting case of intermittency over long ‘ON’ and ‘OFF’ emission states. This pulsar was initially detected in only five epochs over 100 h of telescope time. However, the likelihood of detection seemed to increase with time. Eventually, it was seen to have a longer duty cycle as its spin-

down rate increased (see fig. 6 in Lyne et al. 2017), which points towards magnetospheric changes as the catalyst for the modulation of the ‘ON’ duty cycle. Given the regular nature of the observations both before and after the detection of PSR J1710–3452, any activity cycle similar to the other intermittent pulsars would have resulted in a few detections. A complete lack of detection in all the other epochs indicates a more extreme activity cycle which seems to be unique so far. This is analogous to other transient periodic sources like GLEAM–X J162759.5–523504.3 that was detected for three months with no detections before or after (Hurley-Walker et al. 2022), indicating a strong observational bias against this source population that may be lurking in the Galaxy in large numbers (Beniamini et al. 2022). In addition, the rotation period of 10.4 s puts PSR J1710–3452 in a very different part of the  $P - \dot{P}$  diagram compared to the intermittent pulsars. This part is occupied by a population of magnetars and other intermittent radio emitters like RRATs. The long spin period combined with single-pulses that show quasi-periodic sub-bursts might imply that PSR J1710–3452 belongs to a new category of long-period RENS like PSR J0901–4046 (Caleb et al. 2022b), which have not been observed before due to a severe selection bias. On the other hand, radio-loud magnetars show highly transient radio emission, which could last a month to a few years (Levin et al. 2010; Camilo et al. 2016), yet not necessarily triggered by a high-energy outburst. A recent example is the < 1 month radio-active episode of SGR 1935+2154 (Zhu et al. 2020), seemingly triggered by a timing anomaly (Younes et al. 2023). Hence, PSR J1710–3452 might belong to a class of such magnetars that show transient radio emission not triggered by a high-energy event.

### 4.2 Pulse sub-structure

A small fraction of RENS exhibit sub-bursts in their single-pulses. This microstructure provides insights into the mechanism of the coherent radio emission. Radio-loud magnetars show a diverse range of emission features at radio wavelengths. These are characterized by a long emission envelope (ranging from few tens to a few 100 ms) with a large variability in every rotation. For example, pulses from the radio-loud magnetar XTE J1810–197 show bright, narrow giant pulses, and sub-bursts that are quasi-periodic in nature (Maan et al. 2019; Caleb et al. 2021a; Lower et al. 2021). The radio pulses from PSR J1710–3452 share a lot of traits with radio-loud magnetars. The duty cycle is 10 per cent and the pulses are highly variable and

made up of two main components (PSR J1622–4950; Levin et al. 2012). The trailing component comprises several shorter bursts with pulse widths ranging from 10 to 80 ms (XTE J1810–197; Maan et al. 2022). The ACF and the periodogram show more structure at time-scales between 40 and 60 ms (XTE J1810–197; Caleb et al. 2021a). All these characteristics along with the rotation period indicates that PSR J1710–3452 might be a magnetar.

### 4.3 Old magnetar?

Magnetars are typically a younger class of neutron stars (age  $\sim 10$  kyr) compared to the general population (Kaspi & Beloborodov 2017). Hence, it is expected that most of the magnetars are formed and will still be found in the Galactic plane, which matches the current observations. PSR J1710–3452 has a relatively high Galactic latitude of  $2.91^\circ$ . This would suggest that if PSR J1710–3452 is a magnetar, it is much older when compared to the rest of the population. The lack of any observational evidence for a supernova remnant in the vicinity of PSR J1710–3452 supports this conjecture. Intriguingly, there is only one other magnetar that is above the Galactic plane namely, SGR 0418+5729. It is also the only magnetar that possesses a low-surface magnetic field strength ( $10^{12}$  G) but still emits magnetar-like bursts (Rea et al. 2010). It has been suggested that SGR 0418+5729 is an old magnetar (Rea et al. 2013), which can explain the low magnetic field and the low-surface temperature. If PSR J1710–3452 is also an old magnetar, it could explain the intermittency of the radio emission and its position in the Galaxy. Using this hypothesis, we can get an upper limit on the age of PSR J1710–3452. At a distance of 4 kpc, PSR J1710–3452 lies about 200 pc above the Galactic plane. Using the mean kick velocity of neutron stars of  $150 \text{ km s}^{-1}$  (Hobbs et al. 2005), the limit on the age is  $\leq 2$  Myr. If we take into account the uncertainty on the distance due to the electron density models (typically a factor of 2) and a range of kick velocities from 60 to  $540 \text{ km s}^{-1}$  (Verbunt, Igoshev & Cator 2017), we obtain an age range anywhere between 184 kyr and 6.6 Myr. These estimates would still make PSR J1710–3452 one of the oldest magnetars to be discovered.

This discovery also begs the question whether a large population of these sources exists in the Galaxy. While the discovery of a single object makes a quantification challenging, we estimate an upper limit on the rate of such events with the following assumptions: (1) an active episode with multiple bursts is a single event, (2) since MeerTRAP started observing, such objects have only gone through at least one such episode, and (3) all the MeerTRAP pointings are observed for longer than the typical episode duration. Assuming that such events follow a Poisson distribution across the sky, the 99 per cent confidence upper limit on the number of events following Gehrels (1986) is  $\sim 7$ . Given that the MeerTRAP incoherent beam covers approximately  $1.3^2$  at  $L$  band and assuming that MeerTRAP has spent about 400 d on sky until 2022 July, we obtain an upper limit of  $\sim 560$  events per day per sky. We would like to caution the reader that this rate estimate is a very crude upper limit and a more realistic rate estimate could only be done after a significant number of such sources is discovered in the future.

## 5 CONCLUSION

We have discovered an extremely intermittent radio-emitting neutron star with a rotation period of 10.4 s, which we have localized through radio images. The object was detected in only 1 out of 66 epochs of observations spread over three years suggesting a very narrow activity cycle. The single-pulses show emission properties

reminiscent of radio-loud magnetars but the single epoch detection hinders definitively determining that it has the expected magnetic field strength. No counterpart was detected at any other wavelength. The highly intermittent nature and its position in the Galaxy suggests that PSR J1710–3452 is part of an older population of magnetars which makes it extremely interesting for evolutionary models of neutron stars. The apparent lack of emission over very long time-scales with an extremely narrow activity cycle indicates the presence of a Galactic population of such sources which can be uncovered only through repeated large area sky surveys. It also highlights the potential of image plane searches to find these sources.

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## DATA AVAILABILITY

The data used in this work will be shared with interested parties on reasonable request to the authors.

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