

New upper limits on low-frequency radio emission from isolated neutron stars with LOFAR

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ABSTRACT

Neutron stars that show X-ray and γ -ray pulsed emission must generate electron-positron pairs somewhere in the magnetosphere. Pairs like this are also required for radio emission, which poses the question why a number of these sources appear to be radio quiet. We carried out a deep radio search toward four such neutron stars that are isolated X-ray or γ -ray pulsars, but for which no radio pulsations have been detected so far. These sources are 1RXS J141256.0+792204 (Calvera), PSR J1958+2846, PSR J1932+1916, and SGR J1907+0919. A search at lower radio frequencies, where the radio beam is thought to be wider, increases the chances of detecting these sources compared to the earlier higher-frequency searches. We thus carried out a search for periodic and single-pulse radio emission with the LOFAR radio telescope at 150 MHz. We used the known periods and searched a wide range of dispersion measures because the distances are only poorly constrained. We did not detect pulsed emission from any of the four sources. However, we place highly constraining upper limits on the radio flux density at 150 MHz, of $\lesssim 1.4$ mJy.

Key words. stars: neutron – stars: magnetars

1. Introduction

Through their spin and magnetic field, neutron stars act as powerful cosmic dynamos that can generate a wide variety of electromagnetic emission. There thus exist many subclasses of neutron stars, with different observed behaviors. The evolutionary links between some of the classes are established, while for others, these connections are currently unknown. The largest group in this varied population is formed by the regular rotation-powered radio pulsars. The fast-spinning, high magnetic field population is generally constituted by young pulsars. They show a high spin-down energy-loss rate $\dot{E}$ and a number of energetic phenomena such as radio giant pulse (GP) emission. The most extreme of these fast-spinning and/or high-field sources might also power fast radio bursts (FRBs; e.g., [Pastor-Marazuela et al. 2022](#)). On the long-period outskirts of the P – $\dot{P}$ diagram, slowly rotating pulsars (e.g., [Young et al. 1999](#); [Tan et al. 2018](#)) and magnetars (e.g., [Caleb et al. 2022](#); [Hurley-Walker et al. 2022](#)) sometimes continue to radiate.

Some neutron stars, however, only emit intermittently at radio frequencies. Rotating radio transients (RRATs) burst very irregularly, and most are found near the death line in the P – $\dot{P}$ diagram ([Keane et al. 2011](#)), between the canonical radio pulsars and magnetars. The exact evolutionary connection between RRATs and the steadily radiating normal pulsars is unclear, but studies suggest the presence of an evolutionary link between these different classes (e.g., [Burke-Spolaor 2012](#)).

Finally, populations of neutron stars exist that do not appear to emit in radio at all: radio-quiet magnetars such as most anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs), X-ray dim isolated neutron stars (XDINSs; [Haberl 2007](#)), and γ -ray pulsars (e.g., [Abdo et al. 2013](#)). These are able to produce

high-energy emission, but are often radio quiet. [Gençali & Ertan \(2018\)](#) proposed that RRATs can evolve into XDINSs through a fallback accretion disk, thus becoming radio quiet. However, the magnetar SGR 1935+2154 was recently seen to emit a bright radio burst that bridged the gap in radio luminosities between regular pulsars and FRBs ([CHIME/FRB Collaboration 2020](#); [Bochenek et al. 2020](#); [Maan et al. 2022b](#)). This suggests that magnetars might explain the origin of some, if not all, extragalactic FRBs.

Some of these magnetars might produce radio emission that is only visible at low radio frequencies. Detections of radio pulsations of the γ - and X-ray pulsar Geminga, PSR J0633+1746, have been claimed at and below the 100 MHz observing frequency range ([Malofeev & Malov 1997](#); [Malov et al. 2015](#); [Maan 2015](#)), although a very deep search using the low-frequency array (LOFAR; [van Haarlem et al. 2013](#)) failed to detect any such pulsations ([Coenen 2013](#)). These low-frequency detections offer an intriguing possibility to better understand the radio emission mechanism of these enigmatic objects. Radio detections of a magnetar with LOFAR, complementary to higher-frequency studies such as [Camilo et al. \(2006\)](#) and [Maan et al. \(2022a\)](#) for XTE J1810–197, might offer insight into emission mechanisms and propagation in ultra-strong magnetic fields.

The XDINSs feature periods that are as long as those in magnetars, but their magnetic field strength is less extreme. The XDINSs form a small group of seven isolated neutron stars that show thermal emission in the soft X-ray band. Since their discovery with ROSAT in the 1990s, several attempts failed to detect these sources at radio frequencies (e.g., [Kondratiev et al. 2009](#)). As these campaigns operated above 800 MHz, a sensitive lower-frequency search may be opportune. It has been

Table 1. Parameters of the observed pulsars and observational setup of the observations in the LC3_036 proposal.

	J1412+7922	J1958+2846	J1932+1916	J1907+0919
Right ascension, α (J2000)	14 12 56	19 58 40	19 32 20	19 07 14.33
Declination, δ (J2000)	+79 22 04	+28 45 54	+19 16 39	+09 19 20.1
Period, P (s)	0.05919907107	0.29038924475	0.208214903876	5.198346
Period derivative, $\dot{P}$ (s s ⁻¹)	3.29134×10^{-15}	2.12038×10^{-13}	9.31735×10^{-14}	9.2×10^{-11}
Epoch (MJD)	58150 ^(a)	54800 ^(b)	55214 ^(c)	53628 ^(d)
LOFAR ObsID	L257877	L258545	L259173	L216886
Obs. date (MJD)	57038	57046	57068	56755
Sample time (ms)	0.16384	1.31072	1.31072	0.65536
Test pulsar detected	B1322+83	B1952+29	B1933+16	B1907+10
Periodic flux density (mJy at GHz)	<4 at 0.385 ^(e) <0.05 at 1.36 ^(f) <0.3 at 1.38 ^(e)	<2.0 at 0.15 ^(g) <0.005 at 1.51 ^(b)	<2.9 at 0.15 ^(g) <0.075 at 1.4 ^(e)	50 at 0.111 ^(h) <0.4 at 0.43 ⁽ⁱ⁾ <0.3 at 1.41 ⁽ⁱ⁾ <0.012 @ 1.95 ^(j)
LOFAR periodic sensitivity $S_{\text{lim,p}}$ (mJy)	0.26 ± 0.13	0.53 ± 0.26	0.73 ± 0.36	1.39 ± 0.69
LOFAR single pulse sensitivity $S_{\text{lim,sp}}$ (Jy)	1.47 ± 0.73	1.35 ± 0.68	2.20 ± 1.10	0.84 ± 0.82

Notes. The beam of each observation was centered on the reported pulsar coordinates. The bottom rows list the earlier periodicity and single-pulse search limits. The upper limits from Frail et al. (2016) described in the main text are period-averaged flux densities and are not listed here. The last row lists the limits from the current work for $S/N = 5$, with errors of 50% (Bilous et al. 2016).

References. ^(a)Bogdanov et al. (2019), ^(b)Ray et al. (2011), ^(c)Pletsch et al. (2013), ^(d)Mereghetti et al. (2006), ^(e)Hessels et al. (2007), ^(f)Zane et al. (2011), ^(g)Grießmeier et al. (2021), ^(h)Shitov et al. (2000), ⁽ⁱ⁾Lorimer & Xilouris (2000), ^(j)Lazarus et al. (2012).

proposed (e.g., Komisaroff 1970; Cordes 1978) and observed (e.g., Chen & Wang 2014) that pulsar profiles are usually narrower at higher frequencies and become broader at lower radio frequencies. This suggests that the radio emission cone is broader at low frequencies, and sweeps across a larger fraction of the sky as seen from the pulsar. Additionally, radio pulsars often present negative spectral indices, and are thus brighter at lower frequencies (Bilous et al. 2016). If all neutron star radio beams are broader and brighter at lower frequencies, the probability of detecting radio emission from γ - and X-ray isolated neutron stars (INSs) increases at the lower radio frequencies offered through LOFAR. The earlier observations that resulted in nondetections might then just have missed the narrower high-frequency beam, where the wider lower-frequency beam may, in contrast, actually enclose Earth. In this situation, LOFAR might detect the source.

Recently, a number of radio pulsars were discovered that shared properties with XDINSs and RRATs, such as soft X-ray thermal emission, a similar position in the P - $\dot{P}$ diagram, and a short distance to the Solar System. These sources, PSR J0726–2612 (Rigoselli et al. 2019) and PSR J2251–3711 (Morello et al. 2020), support the hypothesis that XDINS are indeed not intrinsically radio quiet, but that their radio beam points away from us. These shared properties might reflect a potential link between the radio and X-ray emitting pulsars with XDINSs and RRATs. A firm low-frequency radio detection of INSs would thus tie these observationally distinct populations of neutron stars together.

In this work we present LOFAR observations of four INSs that brightly pulsate at X-ray or γ -ray energies, but have not been detected in radio. These sources are listed in Sect. 2, and their parameters are presented in Table 1.

2. Targeted sources

2.1. J1412+7922

The INS 1RXS J141256.0+792204, called “Calvera” and hereafter J1412+7922, was first detected with ROSAT (Voges et al.

1999) as an X-ray point source. It was subsequently detected with *Swift* and *Chandra* (Rutledge et al. 2008; Shevchuk et al. 2009). X-ray observations confirmed its neutron star nature through the detection of $P \approx 59$ ms pulsations by Zane et al. (2011), and allowed for the determination of its spin-down luminosity $\dot{E} \sim 6 \times 10^{35}$ erg s⁻¹, characteristic age $\tau_c \equiv P/2\dot{P} \sim 3 \times 10^5$ years, and surface dipole magnetic field strength $B_s = 4.4 \times 10^{11}$ G by Halpern et al. (2013). Although these values are not unusual for a rotation-powered pulsar, the source is not detected in radio (Hessels et al. 2007; Zane et al. 2011) or γ -rays (Mereghetti et al. 2021). The X-ray emission can be modeled with a two-temperature blackbody spectrum (Zane et al. 2011), similar to other XDINS (Pires et al. 2014). However, the spin period of J1412+7922 is much faster than typically observed in XDINS. Since the source is located at high Galactic latitudes and its inferred distance is relatively small (~ 3.3 kpc; Mereghetti et al. 2021), the path through the interstellar medium is not long enough to explain the radio nondetections by high dispersion measure (DM) or scattering values.

2.2. J1958+2846

Discovered by Abdo et al. (2009) through a blind frequency search of *Fermi*-LAT γ -ray data, INS PSR J1958+2846, hereafter J1958+2846, has shown no X-ray or radio continuum emission counterpart so far (Ray et al. 2011; Frail et al. 2016). Arecibo observations have placed very constraining upper limits of 0.005 mJy at 1510 MHz (Ray et al. 2011). Searches for pulsations from the source using the single international LOFAR station FR606 by Grießmeier et al. (2021) also found no periodic signal.

The double-peaked pulse profile of J1958+2846 can be interpreted as a broad γ -ray beam. The earlier higher-frequency radio nondetections might be due to a narrower radio beam and to an unfavorable rotation geometry with respect to the line of sight. If the radio beam is indeed wider at lower frequencies, LOFAR would have higher chances of detecting it. In this case, a setup

more sensitive than the [Grießmeier et al. \(2021\)](#) single-station search is required.

Modeling by [Pierbattista et al. \(2015\)](#) indicated that the γ -ray pulse profile of J1958+2846 can be well fit by one-pole caustic emission (OPC; [Romani & Watters 2010](#); [Watters et al. 2009](#)) or an outer-gap model (OG; [Cheng et al. 2000](#)). In both cases, the γ -rays are generated at high altitudes above the NS surface. Each model constrains the geometry of the pulsar. For the OPC model, the angle between the rotation and magnetic axes $\alpha = 49^\circ$, while the angle between the observer line of sight and the rotational axis $\zeta = 85^\circ$. The OG model reports similarly large angles, with the NS equator rotating in the plane that also contains Earth, and an oblique dipole: $\alpha = 64^\circ$, $\zeta = 90^\circ$. If this model is correct, the low-frequency radio beam would thus need to be wider than $\sim 30^\circ$ to encompass the telescope. This is uncommonly wide; only 8 out of the 600 pulsars in the ATNF catalog that are not recycled and have a published 400 MHz flux have a duty cycle suggestive of a beam wider than 30% ([Manchester et al. 2005](#)). Because a width like this is unlikely, a total-intensity detection would thus to first order suggest a geometry where α and ζ are closer than follows from [Pierbattista et al. \(2015\)](#), even if this suggestion would only be qualitative. Subsequent follow-up measurements of polarization properties throughout the pulse, and a fit of these properties to the rotating vector model (RVM; [Radhakrishnan & Cooke 1969](#)), can quantify the allowed geometries to within a relatively precise combinations of α and ζ . In a similar study on radio-loud γ -ray pulsars, [Rookyard et al. \(2015\)](#) already reported that RVM fits suggest that the magnetic inclination angles α are much smaller than predicted by the γ -ray light curve models. This in turn confirms that deep radio searches can lead to detections even when the γ -ray light curves suggest that the geometry is unfavorable.

2.3. J1932+1916

The INS PSR J1932+1916, hereafter J1932+1916, was discovered in *Fermi*-LAT data through blind searches with the Einstein at Home volunteer computing system ([Clark et al. 2017](#)). J1932+1916 is the youngest and γ -ray brightest of the four γ -ray pulsars presented from that effort in [Pletsch et al. \(2013\)](#). The period is 0.21 s, and the characteristic age is 35 kyr. [Frail et al. \(2016\)](#) reported no continuum 150 MHz source at this position with GMRT at a flux density upper limit of 27 mJy beam^{-1} , with 1σ errors. If the flux density they found at the position of the pulsar is in fact the pulsed emission from J1932+1916, then a LOFAR periodicity search as described here should detect the source at an S/N of 15 if the duty cycle is 10%. [Karpova et al. \(2017\)](#) reported a potential pulsar wind nebula (PWN) association from *Swift* and *Suzaku* observations. However, no X-ray periodicity searches have been carried out before.

2.4. J1907+0919

The soft gamma repeater J1907+0919, also known as SGR 1900+14, was detected through its bursting nature by [Mazets et al. \(1979\)](#). Later outbursts were detected in 1992 ([Kouveliotou et al. 1993](#)), 1998 ([Hurley et al. 1999](#)), and 2006 ([Mereghetti et al. 2006](#)). The August 1998 outburst allowed the detection of an X-ray period of $\sim 5.16 \text{ s}$, and thus confirmed the nature of the source as a magnetar ([Hurley et al. 1999](#); [Kouveliotou et al. 1999](#)). [Frail et al. \(1999\)](#) detected a transient radio counterpart that appeared simultaneously to the 1998 outburst, and they identified the radio source as a synchrotron-

emitting nebula. [Shitov et al. \(2000\)](#) claimed to have found radio pulsations at 111 MHz from four to nine months after the 1998 burst, but the number of trials involved in the search, the small bandwidth of the system, and the low S/N of the presented plots lead us to conclude that the confidence level for these detections is low. No other periodic emission has been found at higher radio frequencies ([Lorimer & Xilouris 2000](#); [Fox et al. 2001](#); [Lazarus et al. 2012](#)).

This paper is organised as follows: in Sect. 3 we explain how we used LOFAR ([van Haarlem et al. 2013](#)) to observe the sources mentioned above. In Sect. 4 we detail the data reduction procedure, including the periodicity and the single-pulse searches that we carried out. In Sect. 5 we present our results, including the upper limit that we set on the pulsed emission. In Sect. 6 we discuss the consequences of these nondetections for the radio-quiet pulsar population, and in Sect. 7 we conclude.

3. Observations

We observed the four sources with the largest possible set of high band antennas (HBAs) that LOFAR can coherently beam form. Each observation thus added 22 HBA core stations, covering 78.125 MHz bandwidth in the 110 MHz–190 MHz frequency range (centered on 148.92 MHz), with 400 channels that were 195 kHz wide. The LOFAR beam-forming abilities allow us to simultaneously observe different regions of the sky ([van Leeuwen & Stappers 2010](#); [Stappers et al. 2011](#); [Coenen et al. 2014](#)). For our point-source searches of INSSs, we used three beams per observation; one beam pointed to the source of interest, the second beam on a nearby known pulsar, and the third beam as a calibrator blank-sky beam to cross-check potential candidates as possibly arising from radio frequency interference (RFI). We carried out observations between 16 January 2015 and 15 February 2015 under project ID LC3_036¹. We integrated for 3 h on each of our sources. The data were taken in Stokes *I* mode. Since the periods of the γ -ray pulsars are known, the time resolution of each observation was chosen such as to provide good coverage of the pulse period at a sampling time between 0.16–1.3 ms. The observation setup is detailed in Table 1.

4. Data reduction

The data were preprocessed by the LOFAR pulsar pipeline after each observation ([Alexov et al. 2010](#); [Stappers et al. 2011](#)) and stored on the LOFAR Long Term Archive² in PSRFITS format ([Hotan et al. 2004](#)). The 1.5 TB of data was then transferred to one of the nodes of the Apertif real-time FRB search cluster ARTS ([van Leeuwen 2014](#); [van Leeuwen et al. 2022](#)).

We performed a periodicity search as well as a single-pulse search using PRESTO³ ([Ransom 2001](#)). The data were cleaned of RFI using first `rfifind`, and then impulsive and periodic signals at $\text{DM} = 0 \text{ pc cm}^{-3}$ were removed. Next we searched the clean data for periodic signals and single pulses. We searched for counterparts around the known *P* and $\dot{P}$ of each pulsar. Additionally, we performed a full blind search in order to search for potential pulsars in the same field of view because many new pulsars are found at low frequencies ([Sanidas et al. 2019](#)) and

¹ After we completed the current manuscript as [Pastor-Marazuela \(2022\)](#), [Arias et al. \(2022\)](#) posted a preprint presenting partly the same data.

² LTA: <https://lta.lofar.eu/>

³ PRESTO: <https://www.cv.nrao.edu/~sransom/presto/>

serendipitous discoveries happen regularly (e.g., Oostrum et al. 2020). Because the DM of our sources is unknown, we searched over a range of DMs going from 4 pc cm^{-3} to 400 pc cm^{-3} . The DM-distance relation is not precise enough to warrant a much smaller DM range, even for sources for which a distance estimate exists; and a wider DM range allows for discovery of other pulsars contained in our field of view. The highest DM pulsar detected with LOFAR has a $\text{DM} = 217 \text{ pc cm}^{-3}$ (Sanidas et al. 2019). We thus searched up to roughly twice this value to ensure that any detectable sources were covered. We determined the optimal dedispersion parameters with `DDplan` from `PRESTO`. The sampling time variation between some of the four observations had a slight impact on the exact transitions of the step size, but the data were generally dedispersed in steps of 0.01 pc cm^{-3} up to $\text{DM} = 100 \text{ pc cm}^{-3}$, then by 0.03 pc cm^{-3} steps up to 300 pc cm^{-3} , and finally, using 0.05 pc cm^{-3} steps.

We manually inspected all candidates down to $\sigma = 4$, resulting in ~ 1400 candidates per beam. To verify our observational setup, we used the same blind-search technique to our test pulsars B1322+83 and B1933+16, which we detected. The test pulsar B1953+29 was not detected because the sampling time of the observation of J1958+2846 was not adapted to its $\sim 6 \text{ ms}$ period. However, we were able to detect B1952+29 (Hewish et al. 1968) in this same pointing. Even though it is located at $>1^\circ$ from the targeted coordinates, it is bright enough to be visible as a side-lobe detection.

The candidates from the `PRESTO` single-pulse search were further classified using the deep-learning classification algorithm developed by Connor & van Leeuwen (2018), which has been verified and was successful in the Apertif surveys (e.g., Connor et al. 2020; Pastor-Marazuela et al. 2021). This reduced the number of candidates significantly by sifting out the remaining RFI. The remaining candidates were inspected visually.

5. Results

In our targeted observations, we were unable to detect any plausible astronomical radio pulsations or single pulses. We determined new 150 MHz flux upper limits by computing the sensitivity limits of our observations. To establish these sensitivity limits, we applied the radiometer equation adapted to pulsars, as detailed below. We determined the telescope parameters that are input to this equation by following the procedure⁴ described in Kondratiev et al. (2016) and Mikhailov & van Leeuwen (2016). This approach takes the system temperature (including the sky temperature), the projection effects governing the effective area of the fixed tiles, and the amount of time and bandwidth removed due to RFI into account to produce the overall observation system-equivalent flux density (SEFD).

For the sensitivity limit on the periodic emission, we used the following equation (see, e.g., Dewey et al. 1985):

$$S_{\text{lim,p}} = \beta \frac{T_{\text{sys}}}{G \sqrt{n_p} \Delta \nu t_{\text{obs}}} \times S/N_{\text{min}} \times \sqrt{\frac{W}{P - W}}, \quad (1)$$

where $\beta \leq 1$ is a digitization factor, T_{sys} (K) is the system temperature, G (K Jy^{-1}) is the telescope gain, $\Delta \nu$ (Hz) is the observing bandwidth, and t_{obs} (s) is the observation time. P (s) represents the spin period, and W (s) gives the pulsed width assuming a pulsar duty cycle of 10%. To facilitate direct comparison of the periodic emission limits to values reported in Ray et al. (2011)

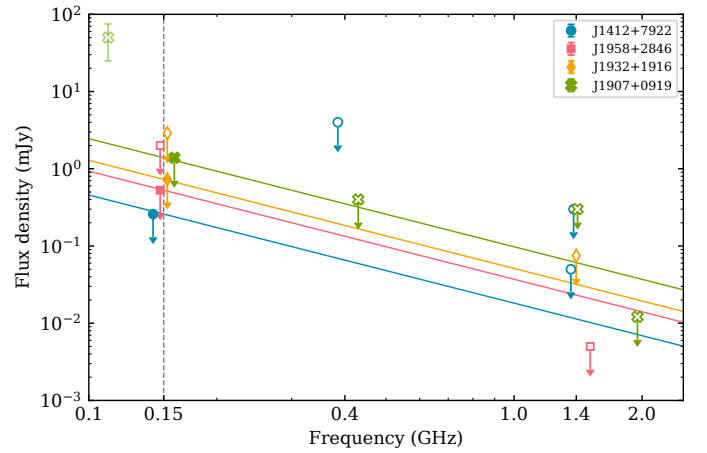


Fig. 1. Flux density upper limits of this work at 150 MHz (filled symbols) with $S/N = 5$ for comparison to earlier searches of the same sources (empty symbols). Solid lines going through our upper limit estimates with spectral index $\alpha = -1.4$ are overlaid to show the scaling of our sensitivity limits. Our limits are plotted slightly offset from the 150 MHz observing frequency (dashed line) for better visibility. The faded green marker for SGR J1907+0919 represents the detection claimed by Shitov et al. (2000).

and Grießmeier et al. (2021), for example, we used a minimum signal-to-noise ratio $S/N_{\text{min}} = 5$. A more conservative option, given the high number of candidates per beam, would arguably be to use a limit of $S/N = 8$. We did, however, review all candidates with $S/N > 4$ by eye and the reported sensitivity limits can be scaled to a different S/N value.

The sensitivity limit on the single-pulse emission, $S_{\text{lim,sp}}$, is computed as follows:

$$S_{\text{lim,sp}} = \beta \frac{T_{\text{sys}}}{G \sqrt{n_p} \Delta \nu t_{\text{obs}}} \times S/N_{\text{min}} \times \sqrt{\frac{t_{\text{obs}}}{W}}, \quad (2)$$

where all variables are the same as in Eq. (2). We searched for single pulses down to a signal-to-noise ratio $S/N_{\text{min}} = 7$.

We report these periodic and single-pulse sensitivity limits, computed at the coordinates of the central beam of each observation, in Table 1. Even though all observations are equally long, the estimated $S_{\text{lim,p}}$ values are different. This is mostly due to the strong dependence of the LOFAR effective area, and hence the sensitivity, on the elevation.

In Fig. 1 we compare our upper limits to those established in previous searches, mostly using the same techniques. Our upper limit on the flux of J1907+0919 is $\sim 50\times$ deeper than the claimed 1998–1999 detections at the same 3m wavelength with BSA (Shitov et al. 2000). Other searches were generally undertaken at higher frequencies (Hessels et al. 2007; Zane et al. 2011; Ray et al. 2011; Pletsch et al. 2013; Grießmeier et al. 2021). When we assume that the radio spectra of these four pulsars are described by a single power-law $S_\nu \propto \nu^\alpha$ with a spectral index of $\alpha = -1.4$ (Bates et al. 2013; Bilous et al. 2016), the upper limits we present here for J1412+7922 and J1932+1916 are the most stringent for any search so far. The upper limits on J1958+2846 (Arecibo; Ray et al. 2011) and J1907+0919 (GBT; Lazarus et al. 2012) are more sensitive than ours by a factor of 2–3. However, pulsars present a broad range of spectral indices. When we take the mean $\pm 2\sigma$ measured by Jankowski et al. (2018), spectral indices can vary from -2.7 to -0.5 . The flux upper limits we measure would be the deepest assuming a -2.7 spectral index, but the shallowest at -0.5 .

⁴ https://github.com/vkond/LOFAR-BF-pulsar-scripts/blob/master/fluxcal/lofar_fluxcal.py

6. Discussion

6.1. Comparison to previous limits

For J1958+2846 and J1932+1916, we can make a straightforward relative comparison between the results we presented here and the existing limit at 150 MHz from the single-station LOFAR campaign by [Grießmeier et al. \(2021\)](#). Our 22 core stations are each one-quarter of the area of the FR606 station and are coherently combined, leading to a difference of a factor $\frac{A_{\text{core}}}{A_{\text{FR606}}} = \frac{22}{4}$ in area A for the radiometer equation and S_{lim} . The integration time t of 3 h is shorter than the FR606 total of 8.3 h (J1958+2846) and 4.1 h (J1932+1916), leading to a factor $\sqrt{\frac{t_{\text{core}}}{t_{\text{FR606}}}} = \sqrt{\frac{3}{8.3}}$ in the radiometer equation. Other factors such as the sky background and the influence of zenith angle on the sensitivity are probably mostly the same for both campaigns. Our S_{lim} is thus $\frac{22}{4} \sqrt{\frac{3}{8.3}} = 3.3$ times deeper than the [Grießmeier et al. \(2021\)](#) upper limit for J1958+2846, and 4.7 times for J1932+1916. These factors agree well with the actual limits listed in Table 1.

[Bilous et al. \(2016\)](#) measured the mean flux density S_{mean} of 158 pulsars detected with LOFAR, where $S_{\text{lim,p}} = S_{\text{mean}} \times \sqrt{W/(P-W)} = S_{\text{mean}}/3$. Compared to these LOFAR detections, our upper limit on J1412+7922 is deeper than all 158 sources (100%), J1958+2846 is deeper than 156 sources (99%), J1932+1916 is deeper than 144 sources (93%), and J1907+0919 is deeper than 109 sources (69%). The flux upper limits we have set on each of the sources in our sample are some of the deepest compared to other LOFAR radio pulsar detections. Longer observing times are thus unlikely to result in a detection or improve our flux upper limits. Additional follow-up would only be constraining with more sensitive radio telescopes.

6.2. Emission angles and intensity

Different pulsar emission mechanism models exist that predict that radio and γ -ray emission is formed simultaneously in the pulsar magnetosphere. The emission sites are not necessarily co-located, however. The periodic radio emission is generally thought to be formed just above the polar cap. The high-energy polar cap (PC) model next assumes that the γ -ray emission is also produced near the surface of the NS and near the magnetic polar caps. In the models of the outer magnetosphere emission, such as the OG or the OPC models, on the other hand, the γ -ray emission is produced high up in the magnetosphere of the NS, within the extent of the light cylinder.

Of the sources in our sample, specific high-energy geometry models have only been proposed for J1958+2846 ([Pierbattista et al. 2015](#)). A detection could have confirmed one of these (Sect. 2.2). Conclusions can be drawn from the nondetections for our sample in general, however. The two general high-energy model classes mentioned above predict different testable beam widths. Our radio nondetections, when attributed to radio beams that are not wide enough to encompass Earth, favor models of the outer magnetosphere (see, e.g., [Romani & Watters 2010](#)). The reason is that in the OG and OPC models, the γ -ray beam (which is detected for our sources) is much broader than the radio beam. The radio beam, being much narrower, is unlikely to cut through our line of sight. This model class is thus more applicable than a class in which the radio and high-energy beam are of similar angular size, such as the PC model (or, to a lesser extent, the slot-gap model; [Muslimov & Harding 2003](#); [Pierbattista et al. 2015](#)). In this case,

detections in both radio and high energy would more often be expected. Our results thus favor OG and OPC models over PC models for high-energy emission.

While it is instructive to discuss the coverage of the radio pulsar beam in binary terms – it either hits or misses Earth – this visibility is not very unambiguous in practice. The beam edge is not sharp. In a beam-mapping experiment enabled by the geometric precession in PSR J1906+0745 ([van Leeuwen et al. 2015](#)), the flux at the edge of the beam is over 100× dimmer than the peak, but it is still present and detectable ([Desvignes et al. 2019](#)). Deeper searches thus continue to have value, even if non-detections at the same frequency already exist. The detection of PSR J1732–3131 only at 327 and potentially even 34 MHz ([Maan & Aswathappa 2014](#)) shows that emission beam widening (or, possibly equivalently, a steep spectral index) at low frequencies is a real effect for γ -ray pulsars as well.

6.3. Emission mechanism and evolution

Most models explain the radio quietness of an NS through a chance beam misalignment, as above. It might also be a more intrinsic property, however. In at least two regions in the P – $\dot{P}$ diagram, radio emission may be increasingly hard to generate.

The first parameter space of interest is for sources close to the radio death line ([Chen & Ruderman 1993](#)). XDINSs are preferably found there, which suggests that these sources are approaching a state in their evolution in which radio emission ceases generally. In normal pulsars, the death line represents the transition into a state in which electron–positron pair formation over the polar cap ceases completely. When the pulsar rotates too slowly to generate a large enough potential drop over the polar cap, as required for this formation, the radio emission stops ([Ruderman & Sutherland 1975](#)). The high-energy emission also requires pair formation, but this could occur farther out. We note that polar-cap pair formation can continue at longer periods if the NS surface magnetic field is not a pure dipole. With this decreased curvature radius, the NS may continue to radiate. Evidence for these higher-order fields is present in a number of pulsars, for instance, PSR J0815+0939 ([Szary & van Leeuwen 2017](#)) and PSR B1839–04 ([Szary et al. 2020](#)). This would also influence the interpretation of any polarization information, as the RVM generally assumes a dipole field.

None of the sources in our sample are close to this death line (see Fig. 2), but SGR J1907+0919 is beyond a different purported boundary: the photon splitting line ([Baring & Harding 2001](#)). In pulsars in this second parameter space of interest, where magnetic fields are stronger than the quantum critical field, 4.4×10^{13} G (Fig. 2), pair formation cannot compete with magnetic photon splitting. These high-field sources might then be radio quiet, but X-ray or γ -ray bright. We mark the critical field line for a dipole in Fig. 2, but we note, as [Baring & Harding \(2001\)](#) did, that higher multipoles and general relativistic effects can subtly change the quiescence limit on a per-source basis. However, based on its spindown dipole magnetic field strength of 7×10^{14} G, our nondetection of SGR J1907+0919 supports the existence of this limit.

6.4. Propagation effects

While the emission-beam widening and the negative spectral index provide potential advantages in a search for pulsars at low frequencies, some propagation effects such as dispersion and scattering intensify there. This hinders the detection of certain sources. The largest pulsar DM detected with LOFAR is

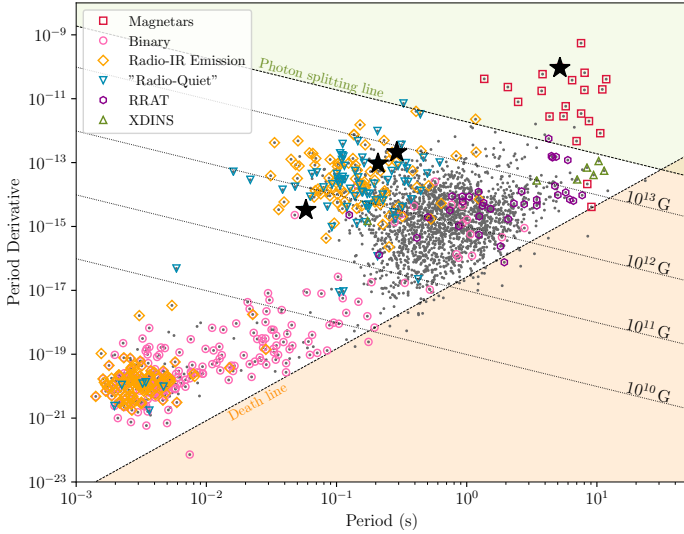


Fig. 2. $P-\dot{P}$ diagram showing the location of the sources presented in this work. All pulsars from the ATNF Pulsar Catalogue (Manchester et al. 2005) are shown as gray dots. Different pulsar classifications are encircled by different symbols. The sources discussed in this work are shown as black stars, from left to right: J1412+7922, J1932+1916, J1932+1916, and J1907+0919. The orange shaded region is delimited by the death line, while the green shaded region is delimited by the photon splitting line. Plot generated with psrqpy (Pitkin 2018).

217 pc cm^{-3} , while many Galactic pulsars are known to have $\text{DM} > 1000 \text{ pc cm}^{-3}$. Although the sources studied in this work do not have radio detections and thus lack a known DM, we can estimate this DM if a hydrogen column density N_{H} were measured from soft X-ray detections. He et al. (2013) reported the correlation between N_{H} and DM as follows: $N_{\text{H}} (10^{20} \text{ cm}^{-2}) = 0.30^{+0.13}_{-0.09} \text{ DM} (\text{pc cm}^{-3})$.

While J1958+2846 and J1932+1916 have only been detected in γ -rays, J1412+7922 and J1907+0919 have soft X-ray detections for which N_{H} has been measured. For J1907+0919, Kouveliotou et al. (1999) measured a high N_{H} value of $3.4\text{--}5.5 \times 10^{22} \text{ cm}^{-2}$. The correlation suggests a DM of $1100\text{--}1800 \text{ pc cm}^{-3}$. At a DM this large, the detection limit of LOFAR is severely impacted. Because J1907+0919 is a very slow rotator, the intra-channel dispersion delay still only is about 10% of the period, which means that periodicity searches might still detect it in principle. The flux density per bin is much decreased when the pulse is smeared out over 100 s of time bins, however.

In contrast, Shevchuk et al. (2009) reported a measured $N_{\text{H}} = 3.1 \pm 0.9 \times 10^{20} \text{ cm}^{-2}$ for J1412+7922. We thus estimate its DM to be in the range $5\text{--}15 \text{ pc cm}^{-3}$. This low DM would easily have been detected with LOFAR.

7. Conclusion

We have conducted deep LOFAR searches of periodic and single-pulse radio emission from four isolated neutron stars. Although we validated the observational setup with the detection of the test pulsars, we did not detect any of the four targeted pulsars. This can be explained with an intrinsic radio-quietness of these sources, as was proposed previously. It might also be caused by a chance misalignment between the radio beam and the line of sight.

With the new upper limits, we can rule out the hypothesis that INSs were not previously detected at radio frequencies around 1 GHz because their spectrum were steeper than that of regu-

lar radio pulsars. Since radio emission from magnetars has been detected after high-energy outbursts (e.g., Maan et al. 2022b), additional radio observations of J1907+0919 if the source reactivates might be successful at detecting single-pulse or periodic emission in the future.

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