Possible periodic activity in the repeating FRB 121102

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ABSTRACT

The discovery that at least some Fast Radio Bursts (FRBs) repeat has ruled out cataclysmic events as the progenitors of these particular bursts. FRB 121102 is the most well-studied repeating FRB but despite extensive monitoring of the source, no underlying pattern in the repetition has previously been identified. Here, we present the results from a radio monitoring campaign of FRB 121102 using the 76-m Lovell telescope. Using the pulses detected in the Lovell data along with pulses from the literature, we report a detection of periodic behaviour of the source over the span of five years of data. The source is currently ‘on’ and we predict it should turn ‘off’ for the approximate MJD range $58947 - 59033$ (2020-04-08 to 2020-07-02), before turning on again for MJD $59033 - 59107$ (2020-07-02 to 2020-09-15). This result, along with the recent detection of periodicity from another repeating FRB, highlights the need for long-term monitoring of repeating FRBs at a high cadence. Using simulations, we show that one needs at least 100 hours of telescope time to follow-up repeating FRBs at a cadence of 1–2 days to detect periodicities in the range of 10–150 days. If the period is real, it shows that repeating FRBs can have a large range in their activity periods that might be difficult to reconcile with neutron star precession models.

Key words: radio continuum:transients – surveys

1 INTRODUCTION

Fast Radio Bursts (FRBs) are bright radio pulses that last for no more than a few milliseconds (Lorimer et al. 2007; Thornton et al. 2013). While their nature is still a mystery, we know they are extragalactic on account of their anomalously high dispersion measures as well as the measured redshifts of the host galaxies of localized FRBs (Tendulkar et al. 2017; Ravi et al. 2015; Bannister et al. 2019). Although subject to large variance at lower redshifts (Masui et al. 2015), the DM acts as a reasonable proxy for distance on cosmological scales (Keane 2018). In spite of detections only at radio wavelengths, the data not only contain information on the intergalactic medium but also about the progenitor and its local environment (Masui et al. 2015).

To date, more than one hundred FRBs have been published (Petroff et al. 2016), yet only some of these have so far been observed to repeat (Spitler et al. 2016a; Shannon et al. 2018; The CHIME/FRB Collaboration et al. 2019; Kumar et al. 2019) and there is no clear evidence favouring a specific progenitor model. The first repeater, FRB 121102, was discovered in 2014 (Spitler et al. 2014) though its repeating nature was not revealed until 2016 (Spitler et al. 2016b). This discovery was crucial as it implied that not all FRB progenitors were of cataclysmic origin. Since then, 19 more repeaters have been discovered (Fonseca et al. 2020; CHIME/FRB Collaboration et al. 2019; Kumar et al. 2019). While the new discoveries suggest the possibility of multiple populations of FRBs, a lack of urgent follow-up and...
monitoring of all known FRBs precludes a definitive conclusion. Of all the repeating sources, FRB 121102 has been studied extensively across a broad range of radio frequencies from 600 MHz (Josephy et al. 2019) to 8 GHz (Gajjar et al. 2019). Though numerous pulses have been detected to date, no underlying pattern has been discovered so far. The shortest separations between two apparently distinctive pulses are 26 s (Gourdji et al. 2019), 34 s (Hardy et al. 2017) and 37 s (Scholz et al. 2016). The recent discovery of periodic activity from FRB 180906.J0158+65 (The CHIME/FRB Collaboration et al. 2020) has rekindled interest in this question and leads us to wonder whether all repeating FRBs show this kind of behaviour. The 16.35-day periodicity in FRB 180906.J0158+65 has led to models being invoked such as; binary orbits to explain the observed periodic behaviour (Lyutikov et al. 2020; Ioka & Zhang 2020) while some authors have proposed a precession of flaring, highly magnetized neutron stars (Levin et al. 2020; Zanazzi & Lai 2020). If true, it will provide a vital clue into the origins of these mysterious bursts. In this paper, we present the results of a long-term monitoring campaign of FRB 121102 using the 76-m Lovell telescope (LT) located at the Jodrell Bank Observatory. The observing campaign is presented in §2. We then describe our search for periodic activity in §3. We discuss the results obtained in §4 before providing concluding remarks in §5.

2 OBSERVATIONS & DATA PROCESSING

Since the discovery of repeating pulses from FRB 121102, it was followed up on a pseudo-regular basis using the LT. Starting from MJD 57363, the source was followed up on a near-weekly cadence, with some daily observations, until December 2016. From that point, it was observed nearly every day through the end of March 2017. After that, there were a few sparse observations until the end of 2018. The cadence of the monitoring campaign was non-uniform, the observations are interspersed with large gaps due to telescope maintenance. The top panel of Figure 1 shows the cadence of observations over the last 4 years. Details of all observations with LT are shown in Table 1.

For each observation, a polyphase filter coarsely channelized a 400 MHz band into 25 subbands of 16 MHz each using a ROACH-based backend (Bassa et al. 2016). Each 16 MHz subband was further channelized into $32 \times 0.5$ MHz channels using digifil from the dapr software suite (van Straten & Bailes 2011), and downsampled to a sampling time of 256 µs. The 800 total channels, spanning 400 MHz, were then combined in frequency. After MJD 57729, all observations (75% of data reported here) had a bandwidth of 336 MHz, to mitigate the effect of radio-frequency interference (RFI) on the data. We also masked frequency channels in the data containing narrow-band RFI. No other RFI mitigation algorithm was used to massage the data. We searched these data using the single-pulse-search software package HEIMDALL$^1$ that searches for single pulses over a timeseries generated for a range of trial DMs using a brute-force dedispersion algorithm. We used a DM range of 0 to 800 pc cm$^{-3}$ and searched over widths ranging from 256 µs up to 32 ms. Candidates from HEIMDALL were classified with the FETCH machine-learning candidate classifier (Agarwal et al. 2019), and all candidates classified as astrophysical pulses, with a signal-to-noise ratio (S/N) greater than 8, were viewed by eye to verify they were real, astrophysical pulses from FRB 121102. From this analysis, we detected 25 pulses in the data. To look for fainter pulses, we visually inspected all candidates down to a S/N of 6; 7 more pulses were found. FETCH misclassified five of the seven low S/N pulses as the neural network is not trained on any pulses with S/N less than 8. For each pulse, the cleaned data were dedispersed at the S/N optimized DM. We know that the true DM of this source is different owing to structure in the radio emission that varies over time and frequency (Hessels et al. 2019). Since structure analysis is not the focus of this paper, we decided to dedisperse the pulses to maximise the S/N. The resulting timeseries were convolved with a series of Gaussian templates over a range of widths using a python based package SPYDEN$^2$ to obtain the best-fit S/N and width for each pulse. Then, we computed the fluence for each pulse using the radiometer equation ( Lorimer & Kramer 2004). For a given S/N and width, W, the fluence,

$$F = \frac{S}{\sqrt{G T_{\text{sys}} W / n_p \Delta v}}.$$  

where G is the telescope gain ($G \approx 0.9$) in units of K Jy$^{-1}$, $T_{\text{sys}}$ is the system temperature that is the summation of the receiver temperature and the sky temperature at the centre frequency of the receiver in Kelvin, $n_p = 2$ is the number of polarizations to be summed and $\Delta v$ is the bandwidth in Hz. The calculated parameters for each pulse are presented in Table 2.

3 PERIODICITY

Table 2 shows the observed parameters of the detected FRBs in the monitoring campaign. The time-span of more than two years enabled us to study in detail the long term emission variability of FRB 121101. The top panel of Figure 1 shows the LT detections along with the observing dates over the entire campaign. Visually, we noticed a pattern in the detection of pulses from FRB 121102. To make sure that we are

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1 https://sourceforge.net/projects/heimdall-astro/

2 https://bitbucket.org/vmorello/spyden/src/master/

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Table 1. Start and end MJDs for all observations with the LT and the number of detections in each observing session. The full table can be found in the the online supplementary materials.
not biased by unevenly sampled observations, we ran a two sample Wald-Wolfowitz runs test (Alhakim & Hooper 2008) on the LT sample of pulses. This test evaluates whether a given sequence of binomial outcomes is likely to be drawn from a random distribution. Hence, for a given sequence of events with two outcomes, the test statistic,

$$Z = \frac{R - \bar{R}}{S_R},$$

where $R$ is the observed number of runs, $\bar{R}$ is the expected number of runs and $S_R$ is the standard deviation of runs. $Z$ can then be tested against the null hypothesis by compar-
To overcome this, we computed the periodogram even though the sampling is non-uniform (see Scargle 1982). Since the LT observations are spread along a long baseline and tend to be densely sampled closer to periods of activity, a periodogram of the resulting timeseries was biased. One needs to sample multiple active and inactive periods to get a correct period from the periodogram even though the sampling is non-uniform (see VanderPlas 2018, for more details). To do this, we used a Fast Folding Algorithm (FFA) to search for periodicity in the activity of the source. The FFA is designed to search for periodic pulsar signals in time series data, and provides the highest possible period resolution for that purpose (Staelin 1969). To make the algorithm applicable to our data set, we first binned the list of detected pulse MJDs available in the literature, 138 MJDs in total from Spitler et al. (2014); Hardy et al. (2017); Gourdji et al. (2019); Spitler et al. (2016b); Gajjar et al. (2018b); Oostrum et al. (2019) and this paper (see Table 3 for more details), into a histogram with a time resolution of 0.05 days. We don’t use the most recent active phase that was reported by multiple telescopes (Di et al. 2019; Pearlman et al. 2019; Caleb et al. 2019) used in this paper. Full table can be found in the online supplementary materials.

| ID | Topocentric MJD | Fluence | Width | S/N | DM |
|----|-----------------|---------|-------|-----|----|
| 0  | 56233.282837007905 | Spitler et al. 2016 |
| 1  | 57159.737600835 | Spitler et al. 2016 |
| 2  | 57159.744223619 | Spitler et al. 2016 |
| 3  | 57175.6931432325005 | Spitler et al. 2016 |
| 4  | 57175.699727825595 | Spitler et al. 2016 |
| 5  | 57175.742576706 | Spitler et al. 2016 |
| 6  | 57175.74283944006 | Spitler et al. 2016 |
| 7  | 57175.743510388 | Spitler et al. 2016 |
| 8  | 57175.745665832 | Spitler et al. 2016 |
| 9  | 57175.747624851 | Spitler et al. 2016 |
| 10 | 57175.748287265 | Spitler et al. 2016 |

Table 3. MJDs of the first 10 published pulses of FRB 121102 used in this paper. Full table can be found in the online supplementary materials.
4 DISCUSSION

4.1 Periodic Activity?

Due to the sparse and uneven observing coverage of the whole time span considered (Fig. 1), we cannot reasonably assume that the pulse detection dates are uniformly distributed in phase under the null hypothesis (i.e., the source exhibits no periodic activity pattern) for a period $P_0 = 159$ days. To estimate that distribution, an exhaustive list of the start and end dates of all attempted observations would be required, but is not available since typically, only detected pulse MJDs are published in the literature. The statistical significance of our detected periodicity thus cannot be rigorously estimated with the data currently available, and should be treated circumspectly as it may result from a chance alignment between the time ranges where no observations have been made. We acknowledge that bootstrapping the available detections can give some sort of a significance for the detected peak but the main caveat of this method is the assumption that all the observations conducted in a given time period are randomly distributed over the entire time period. This is not true with follow-ups of repeating sources as telescopes tend to observe these sources with denser cadence when there is a previously known detection. We also note that if the periodic activity in FRB 121102 is in any way similar to FRB180916.J0158+65, one would expect the source to not emit in every single active phase. This can also result in reduction in the significance of detection of periodicity.

Our best-fit parameters suggest that the next two activity periods should occur in the MJD ranges 58873–58947 (2020-01-25 to 2020-04-08) and 59033–59107 (2020-07-02 to 2020-09-15). We particularly encourage further observations during the predicted quiescence period in-between, as they could falsify our periodicity claim. A confirmation will require extending the baseline of observations, preferably with a regular cadence. How to optimally space observations to search for, or confirm periodicity of a repeating source is a question that deserves further examination. In essence, a large number of cycles need to be sampled before any proper statistical analysis on the significance of detection can be performed.

If the detected period is astrophysical in origin, it has implications on the possible progenitors of repeating FRBs. The CHIME/FRB Collaboration et al. (2020) have invoked orbital motion to cause such periodicities. If we consider also orbital motion to be the cause of the observed periodicity in FRB 121102, the large range in the observed periods (16–160 days) can constrain the possible binary systems. High-mass X-ray binaries are systems with a neutron star in an orbit with a massive O/B star. HMXBs in our Galaxy and the Small Magellanic Cloud have a large range of orbital periods, ranging from a few tens to hundreds of days (see Liu et al. 2006, for more details). Ioka & Zhang (2020) propose a model where the magnetized neutron star is combed by the highly energetic wind of the secondary star. Massive stars in HMXB systems tend to possess energetic winds for this scenario to be feasible. On the other hand, binaries where the donor star fills the Roche lobe of the system have much shorter periods (< 10 days) and are unlikely to be possible progenitors. Other progenitor models invoke precessing neutron stars or young flaring magnetars (Levin et al. 2020; Zanazzi & Lai 2020). The authors of these studies expect the timescale of precession to be of the order of weeks though larger precession periods (a few months) would be harder to explain as the internal magnetic field would have to be lower by at least an order of magnitude compared to the expected internal fields in young magnetars and will have implications on the observed burst energies from these sources (Levin et al. 2020). To draw any inferences about the origin of this repeating class of FRBs, regular monitoring of such sources is imperative along with more discoveries of periodic FRBs and a systematic approach to following up known repeaters with existing instruments can achieve this goal.

4.2 Follow-up Strategies

The analysis of FRB 121102 detections begs the question of whether all repeating sources of FRBs exhibit periodic activity. If we assume this to be the case, it has implications on follow-up strategies of future discoveries of repeating FRBs. We note that transit instruments such as CHIME will have an advantage over other steerable radio telescopes as transit instruments will automatically get a cadence of one day as the source transits in the beam of the telescope. In spite of this advantage, it is possible to get an optimized follow-up strategy for other single dish telescopes and interferometers. To that end, we ran a simulation to optimize follow-up strategies of periodic FRBs. To make our simulations agnostic to different observatories and different sensitivities, we assign unity weight to all observations where we detect a burst and zero weight when there is a non-detection. We assume that the bursts follow a Poissonian distribution in the active period with a repetition rate of 1.1 bursts per hour at 1.4 GHz (Houben et al. 2019). During an active period, for each observing session, we draw from a binomial probability distribution to check if a pulse was detected. The probability of detecting $N$ bursts for a given observing session of duration $T_{obs}$.

$$P(X = N) \approx \frac{(RT_{obs})^N e^{-RT_{obs}}}{N!},$$

(3)

where, $R$ is the repetition rate. Hence, the probability to detect any $N > 0$, $P(N > 0) = 1 - e^{-RT_{obs}}$. We use this computed probability to draw from the binomial distribution to get the number of observing sessions within the activity period where there was a detection. This way, we take into account the sporadic nature of FRBs during an active period. Then, for a given activity period, we can obtain a sequence of detections and non-detections for our follow-up campaign over a range of separations between observations.
Figure 2. Periodogram obtained by running a Fast Folding Algorithm (FFA) on an evenly sampled, high time-resolution histogram of the detected pulse MJDs. The folded profiles produced by the FFA were evaluated by the length (relative to the trial period) of the longest contiguous phase region without detectable activity. At the most significant trial period, \( P_0 = 159.3 \) days, the source is active only for a contiguous 47% of a hypothetical cycle.

Figure 3. Detected pulse MJDs folded at the best-fit period of \( P_0 = 159 \) days. A phase of zero corresponds to the reference MJD \( t_{\text{ref}} = 58200 \).

For the follow-up campaign, we assume that each observing session is one hour long. We computed the periodogram of the detections in the observing campaign. To assess the significance of the detections, we generated a folded profile from the obtained sequence of detections and ran a goodness of fit test on it for a null hypothesis that the folded profile is uniform across the entire period. We use the reduced \( \chi^2 \) as the test statistic to evaluate the deviation of the resulting profile from the null hypothesis. We note that there is an underlying assumption here that all events within a phase bin of the folded profile follow Gaussian statistics which may not necessarily be true (see The CHIME/FRB Collaboration et al. 2020, for more details). We use a reduced \( \chi^2 \) of 7.0 as a threshold for the detection of a period at a 5-\( \sigma \) level of significance after taking into account the number of trial periods searched. Since time on a telescope for such follow-up observations is limited, we ran this analysis for different amounts of allocated time on a any given radio telescope. Figure 4 shows the reduced \( \chi^2 \) as a function of separation of observations for four different allocated times. One can clearly see that to obtain an accurate and significant detection of periodicity, one needs to have a fairly dense cadence of observations. Moreover, to have any chance of detecting a periodicity ranging from 10–150 days, at least 100 hours of telescope time is needed to follow-up potential repeating FRBs at a cadence of 1–2 days between observations.

5 CONCLUSIONS

We have carried out a long-term radio monitoring campaign of FRB 121102 with the Lovell Telescope. Using these pulses and other detections from the literature, we performed a periodicity search and detected a tentative period of 159 days in the periodogram with a duty cycle of 47%. We extrapolated the computed period to the most recent activity and show that the detections lie within the activity phase predicted by the period. We do note that the uneven observing strategy prevents us from determining a robust significance of the detection of the said period. To avoid these issues in the future, we performed simulations of periodic FRBs to show that single dish telescopes need at least 100 hours of follow-up time to determining periodicities in these sources. This shows that single dish telescopes and interferometers will be able to follow-up repeating FRBs in reasonable amount of telescope time to detect periodicities. Our study also shows the importance of reporting non-detections for any repeating FRB follow-up campaigns as they are crucial for computing the robustness of any detected periodicity. If the periodicity in FRB 121102 is genuine, it suggests that there is a large range in the periodicities of repeating FRBs and more periodic FRBs need to be discovered to infer the nature of their progenitors.

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Figure 4. Reduced $\chi^2$ as a function of separation between observations for different total allocated telescope times displayed in different panels. Different lines correspond to FRBs with different periods shown in the legend. The black stars with red outlines correspond to the reduced-$\chi^2$ values obtained by CHIME for different periods (x-axis on the top of the panels) for a separation of 1 day and a source transit time of 15 minutes. The dashed magenta line corresponds to the reduced $\chi^2$ corresponding to a 5-$\sigma$ detection of the periodicity. The vertical dashed lines correspond to the minimum separation before a pulse is detected.
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