SGR-like behaviour of the repeating FRB 121102

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Abstract. Fast radio bursts (FRBs) are millisecond-duration radio signals occurring at cosmological distances. However the physical model of FRBs is mystery, many models have been proposed. Here we study the frequency distributions of peak flux, fluence, duration and waiting time for the repeating FRB 121102. The cumulative distributions of peak flux, fluence and duration show power-law forms. The waiting time distribution also shows power-law distribution, and is consistent with a non-stationary Poisson process. These distributions are similar as those of soft gamma repeaters (SGRs). We also use the statistical results to test the proposed models for FRBs. These distributions are consistent with the predictions from avalanche models of slowly driven nonlinear dissipative systems.

Keywords: gamma ray theory, millisecond pulsars

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1 Introduction

Fast radio bursts (FRBs) are intense radio flashes occurring at high Galactic latitudes with anomalously high dispersion measure (DM) [1–5]. Due to the lack of distance information, their physical origin is unknown. Some people suggested that the high DM is dominated by the ionized intergalactic medium, which implies that FRBs may occur at cosmological distances.

Recently, Keane et al. (2016) claimed to discover the first FRB host galaxy, which is an elliptical galaxy at $z = 0.492 \pm 0.008$ [6]. However, this conclusion was questioned by some subsequent papers [7, 8]. More recently, using fast-dump interferometry with the Karl G. Jansky Very Large Array (VLA), the host galaxy of repeating FRB 121102 was discovered [9, 10]. Optical imaging and spectroscopy identify FRB 121102 a redshift of $z = 0.19273$ [10]. The cosmological origin of FRB 121102 is confirmed. Therefore FRBs are promising cosmological probes. However, the physical origin of FRBs is mysterious until now. Many theoretical models for FRBs are proposed, including collapses of supra-massive neutron star into black hole [11–13], magnetar pulse-wind interactions [14], charged black hole binary mergers [15], giant pulse emissions from pulsars [16], giant flares from magnetars [17–21], unipolar inductor model [22], and double neutron stars mergers [23]. The FRB 121102 is repeating, which disfavors models involving cataclysmic events [24]. Additional six bursts [25] and nine bursts [9] for FRB 121102 are detected. So there may be two populations of FRBs [24, 26, 27]. Dai et al. (2016) proposed that the repeating bursts are produced by lots of asteroids encountering with highly magnetized pulsar [28]. A neutron star-white dwarf binary model also has been proposed for the repeating FRB 121102 [29].

Until now, twenty six bursts of FRB 121102 have been observed. However, the nine bursts discovered by VLA are not observed by Arecibo observatory. In this paper, we investigate the frequency distributions of peak flux, fluence, duration and waiting time for FRB 121102. We also test the proposed models for FRBs using the derived distributions. This paper is organized as follows. The frequency distributions are shown in section 2. In section 3, we test theoretical models for FRBs using the statistical results. Finally, the conclusion and discussions are given in section 4.

2 Frequency distributions of burst parameters

For FRB 121102, we use the parameters of eleven bursts from [24] and six bursts from [25], which are listed in table 1. Because the nine bursts observed by VLA in the 2.5–3.5 GHz [9], and these bursts are not detected by Arecibo, only the upper limit is given. These nine
bursts are not considered in our analysis. The eleven bursts in [24] are discovered by William E. Gordon Telescope at the Arecibo Observatory and the 7-beam Arecibo L-band Feed Array (ALFA). The ALFA is a seven-beam receiver operating at 1.4 GHz with 0.3 GHz bandwidth [30]. The antenna gains for these beams are different, i.e., 10.4 K Jy$^{-1}$ for the central beam at low zenith angles and 8.2 K Jy$^{-1}$ for the other six beams [30]. Because the bursts could be detected by different beams, the observed flux or fluence must be corrected. Only the last six bursts are pointing to the central beam [24], so the fluxes and fluences of other five bursts are normalized to the central beam by multiplying a factor of 1.268. The additional six bursts are observed by Green Bank Telescope and the single-pixel L-Wide receiver at Arecibo observatory [25]. Therefore, the fluxes of these bursts are intrinsic. For each bursts, Column 2 gives the peak time of each burst listed in Column 1. The peak flux is presented in Column 3 in unit of Jy. Column 4 gives the fluence $F$ of each burst in unit of Jy ms. The observed duration time of burst is given in Column 5. The waiting time is given in Column 6. The waiting time $\Delta t$ is defined as the difference of occurring times for two adjacent bursts, and can be calculated from the time difference of Column 2. Only the continues observation is considered. When calculating the waiting time, the peak flux limit 0.02 Jy is considered. Because the detection threshold of ALFA is about 0.02 Jy [24, 25]. The definition of waiting time is widely used in solar physics and astrophysics.

The number of bursts $N(F)dF$ with fluence between $F$ and $F+dF$ can be expressed by

$$N(F)dF \propto F^{-\alpha} dF,$$

(2.1)
where $\alpha_F$ is the power-law index. The number of bursts for FRB 121102 is small. Rather than examining the differential distribution directly, it is preferable to plot the cumulative distribution, which can avoid binning of the data. Because the width of binning can affect the fitting result. Integrating equation (2.1), we obtain the cumulative distribution of fluence

$$N(> F) \propto \int_F^\infty F^{-\alpha_F} dF \propto F^{-\alpha_F+1}.$$  

(2.2)

For the peak flux $S$, the differential frequency distribution is

$$N(S) dS \propto S^{-\alpha_S} dS.$$  

(2.3)

So the number of FRBs with peak flux larger than $S$ is

$$N(> S) \propto \int_S^\infty S^{-\alpha_S} dS \propto S^{-\alpha_S+1}.$$  

(2.4)

We apply the Markov Chain Monte Carlo (MCMC) method to derive the best-fitting parameters. In astrophysical observations, count statistics is often limited. The bursts of FRB 121102 is 17. Such low count number does not fulfill the condition required for the Gaussian approximation, a well approximation is the Poisson distribution. Consider the number of observed events $N_{\text{obs}}$ following Poisson distribution, the likelihood function for MCMC method can be expressed as

$$L(\theta) = \sum_i \ln(P_i(N_{\text{obs},i}))$$

$$= \sum_i (N_{\text{obs},i} \ln(N_{\text{th}}(\theta)) - \ln(N_{\text{obs},i}) - N_{\text{th}}(\theta)),$$  

(2.5)

where $\theta$ is the parameter in the model to be constrained by the observed data, $N_{\text{obs},i}$ is the $i$th observed data, and $N_{\text{th}}$ is the theoretical number predicted by model. For the cumulative distribution, it has $N_{\text{obs},i} = i$. Therefore, the likelihood can be re-expressed as $L(\theta) = \sum_{i=1}^{N_{\text{obs,tot}}} (i \ln(N_{\text{th}}(\theta)) - \ln(i) - N_{\text{th}}(\theta))$, where $N_{\text{obs,tot}}$ is the total number of observed events. We use a python package pymc [31] to apply the MCMC method to optimize the parameters of theoretical distributions. In the fitting, we consider the priors of all the parameters $\theta$ as uniform distributions in a relatively large range, because the priors are not important when sampling enough samples with MCMC method. We must note that the events in each bin of the differential distribution are independent, but the number of events $N(> x)$ in the cumulative distribution are statistically dependent. Fortunately, we use a logarithmic binning, the fluctuations of events for cumulative distribution in each bin, may follow approximately the same random statistics $\sigma_{\text{cum},i} = \sqrt{N_{\text{cum},i}}$ in each bin as for the differential distribution. So the likelihood function of equation (2.5) may be a well approximation. This problem has been extensively discussed in [32]. Figure 1 shows the cumulative distributions of fluence (left panel) and peak flux (right panel) for seventeen bursts of FRB 121102, respectively. The power-law index for fluence is $\alpha_F = 1.80 \pm 0.15$ with 1$\sigma$ confidence level. The value of $\alpha_F$ is from 1.5 to 2.2 [33]. While, for peak flux, the power-law index is $\alpha_S = 1.07 \pm 0.05$ with 1$\sigma$ confidence level.

The differential distribution of duration time $W$ can be expressed as

$$N(W) dW \propto W^{-\alpha_W} dW.$$  

(2.6)
Figure 1. The cumulative distributions of fluence (left panel) and peak flux (right panel) for FRB 121102, respectively. The best-fitting power-law indices are $\alpha_F = 1.80 \pm 0.15$ and $\alpha_S = 1.07 \pm 0.05$ for fluence and peak flux, respectively.

Figure 2. The cumulative distributions of duration (left panel) and waiting time (right panel) for FRB 121102, respectively. The best-fitting power-law indices are $\alpha_W = 1.95 \pm 0.32$ and $\alpha_{WT} = 1.09 \pm 0.05$, respectively.

So the cumulative distribution of duration time $W$ is

$$N(>W) \propto \int_W^{W_{\text{max}}} W^{-\alpha_W} \, dW \propto W^{-\alpha_W+1} - W_{\text{max}}^{-\alpha_W+1},$$

where $W_{\text{max}}$ is the maximal duration time. The Markov Chain Monte Carlo (MCMC) method is also used to derive the best-fitting parameters simultaneously. Left panel of figure 2 presents the cumulative distribution of duration for FRB 121102. From this panel, a maximal duration time is obviously shown. The best-fitting power-law index and maximal duration time are $\alpha_W = 1.95 \pm 0.32$, and $W_{\text{max}} = 9.80 \pm 0.35$ with 1σ confidence level, respectively. It should be noted that the observed duration time will be broadened when radio waves propagate through a plasma. The scatter-broadening time of a pulsed signal depends on the DM and the observing frequency, and an empirical function is given [34]. However, there is no clear evidence for scatter broadening of FRB 121102 [24].

If the burst rate is constant, the waiting-time distribution is the Poisson interval distribution [35]

$$P(\Delta t) = \lambda e^{-\lambda \Delta t}$$
where $\Delta t$ is the interval between events, and $\lambda$ is the burst rate. If the burst rate is time varying, the waiting time distribution can be treated as a combination of piecewise constant Poisson processes. Generally, for most forms of $\lambda(t)$, the waiting time distribution can be shown as power-law form [36]

$$P(\Delta t) \propto \Delta t^{-\alpha_{WT}}. \quad (2.9)$$

In order to avoid binning of the data, the cumulative waiting time distribution is given by

$$N(> \Delta t) \propto \int_{\Delta t}^{\Delta t_{\text{max}}} \Delta t^{-\alpha_{WT}} dW \propto \Delta t^{-\alpha_{WT}+1} - \Delta t_{\text{max}}^{-\alpha_{WT}+1}. \quad (2.10)$$

For FRB 121102, the observation is not continues [24, 25]. The detailed observations by different telescopes are shown in figure 1 of [25]. Therefore, in order to obtain reliable waiting times, we select the waiting times during periods of continuous observation. We use the waiting times presented in table 1 of [29]. There are ten waiting times from tens to hundreds of seconds. Right panel of figure 2 shows the cumulative waiting time distribution of FRB 121102. The best-fitting power-law index and maximal waiting time are $\alpha_{WT} = 1.09 \pm 0.05$, and $\Delta t_{\text{max}} = 1020.18 \pm 10.25$ s with $1\sigma$ confidence level.

### 3 Comparing with predictions of theoretical models

The power-law distributions indicates the stochastic engine for FRB 121102. There are many models proposed to explain the properties of FRBs. In this section, we will test theoretical models predictions with statistical results.

Dai et al. (2016) proposed that the repeating bursts can be produced from lots of asteroids encountering with highly magnetized pulsar [28]. In order to explain observation, the diameters of asteroids are small, i.e., $L < 5$ km [28]. From their equation (2.2), the differential frequency distribution of diameter $L$ of asteroids is predicted to $dN/dL = dN/dW \times dW/dL$, with duration time $W$. So if the index for differential frequency distribution of duration is $-2.0$, the value is $dN/dL \propto L^{-7/3}$. From the observation of Sloan Digital Sky Survey, the a broken power law was found with $dN/dL \propto L^{-4}$ for large asteroids (5–50 km) and $dN/dL \propto L^{-2.3}$ for smaller asteroids (0.5–5 km) [37]. The differential size distribution of small asteroids is $dN/dL \propto L^{-2.29}$ [38]. These value are well consistent with the model prediction.

Cordes and Wasserman (2016) suggested that FRBs originate from Crab-like giant pulses of extragalactic neutron stars [16]. The index of peak flux cumulative distribution $\alpha_S$ is from 1.3 to 2.5. The low limit is a little larger than the best-fitting value. Lyutikov et al. (2016) argued that FRBs, including repeating and non-repeating FRBs, are from giant pulses of young rapidly rotating pulsars [39]. In their model, the intrinsic luminosity of an FRB is proportional to the spin-down power of neutron star. So the predicted distribution of FRB flux is $N(> S) \propto S^{-3/2}$ [39]. From our statistical study of 17 bursts of FRB 121102, the cumulative distribution $N(> S) \propto S^{-1.06}$ is found, which is different from their model prediction. So the repeating FRB 121102 may disfavor the rotationally powered model. The distance measurement of the repeating FRB 121102 also ruled out rotationally-powered radio emission [40].

Katz (2016) proposed that FRBs are generated by magnetic energy released in magnetar magnetospheres [41]. Metzger et al. (2017) also argued that the repeating FRB 121102 is powered by millisecond magnetar, through its rotational or magnetic energy [42]. From observational constraint, the magnetic energy is favored [42]. Generally, the soft gamma repeater
Figure 3. The differential distributions of duration (left panel) and waiting time (right panel) for SGR 1806-20, respectively. The best-fitting power-law indices are $\alpha_W = 2.14 \pm 0.22$ and $\alpha_{WT} = 0.95 \pm 0.05$, respectively.

(SGR) outbursts result from the dissipation of magnetostatic energy in the magnetosphere of magnetars. So we compare the statistical properties of FRB 121102 and SGR 1806-20. Figure 3 shows the differential distributions of duration (left panel), and waiting time (right panel) for SGR 1806-20. We use the waiting time data from [43], and duration time data from [44]. The best-fitting indices are $\alpha_W = 2.14 \pm 0.22$ and $\alpha_{WT} = 0.95 \pm 0.05$ for duration time and waiting time, respectively. The distribution of SGR 1806-20 burst energies follows a power-law $dN \propto E^{-\gamma}dE$ with $\gamma \sim 1.6$ [45, 46]. These indices are well consistent with those of FRB 121102. This may indicate that repeating FRBs may be related to extremely magnetized neutron stars. Besides these statistic distributions, there are some phenomenological similarity between FRBs and SGRs. First, they are both repeating. At least, FRB 121102 show repeating bursts [9, 24, 25]. Second, the duty factor $D = \langle f(t) \rangle^2 / \langle f(t)^2 \rangle$ with flux $f(t)$ is similar, $D \sim 10^{-10}$ for SGRs and $D < 10^{-8}$ for FRBs [41, 47]. This value denotes the the fraction of the time in which a source emits at close to its peak flux.

4 Discussions and conclusion

In this paper, we study the statistical properties of repeating FRB 121102, including peak flux, fluence, duration time and waiting time. The cumulative distributions of peak flux, fluence and duration show power-law forms. The waiting time distribution also shows power-law distribution, and is consistent with a non-stationary Poisson process. Power-law size distributions have been discovered in many astrophysical phenomena, which may indicate a stochastic central engine. We also compare the statistical results with theoretical models predictions. The duration distribution from theoretical model relating asteroids encountering with highly magnetized pulsar is consistent with observations. Similar distributions between FRB 121102 and SGR 1806-20, such as fluence, duration and waiting time, also support the models proposed by [41], in which the magnetic energy releases in magnetar magnetospheres. So more observation is needed to distinguish these two models.

Power-law distributions of events have been discovered in a large number of astrophysical phenomena in many wavelengths [for a recent review, see 48]. The power-law frequency distributions, including peak flux, fluence, duration and waiting time, are predicted by self-organized criticality (SOC) systems [48–50]. These distributions also satisfy the criteria that
define a SOC system [48], which occurs in many natural systems that exhibit nonlinear energy dissipation [48, 51, 52]. Therefore, FRBs may also be avalanche events.

In future, some facilities, such as Chinese Five-hundred-meter Aperture Spherical radio Telescope (FAST) [53], Canadian Hydrogen Intensity Mapping Experiment (CHIME) [54], the Square Kilometer Array, or other upcoming wide-field telescopes, will collect a large number of FRBs. The statistics of FRBs will give constraints on the nature of central engine.

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