Updated constraints on superconducting cosmic strings from the astronomy of fast radio bursts

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In this article, we study the updated constraints upon the radio transient signals arisen from superconducting cosmic strings (SCSs) in light of the recent observational developments of fast radio bursts (FRBs) astronomy. By assuming that the currents in these strings follow the Poisson distribution, we show that two parameters can be severely limited by FRB experiments, which are the characteristic tension and current of cosmic strings, respectively. In particular, we investigate data sets from two FRB experiments namely: Parkes and ASKAP. Our analyses show that, Parkes jointly with ASKAP can constrain the parameter space for superconducting cosmic strings well enough. Our numerical calculation estimates that the possibly allowed parameter space for strings are give by $G\mu \sim [10^{-16}, 10^{-13}]$ and $I_c \sim [10^0, 10^2] \text{GeV}$.

I. INTRODUCTION

Since the first observation of the fast radio transient phenomenon in the universe [11], the astronomy of fast radio bursts (FRBs) has attracted broad interests of scientists from both the observational and theoretical perspectives [2, 3]. Due to their large dispersion measures and bright pulses, many researchers attempt to investigate these mysterious signals from cosmological interpretations. Different theoretical models have been proposed to understand the possible origin of these FRB signals [4], namely, synchrotron maser emission from young magnetars in supernova remnants [5], radiation from cosmic string cusps [6], or from charged primordial black hole binaries coalescence [7], as well as other hypothetical origins [8–11]. A major effort has been made to establish the broad-band, wide-field surveys in purpose of hunting for FRB events from the perspective of observational astronomy. These radio bursts have been detected by Parkes [12–15], Arecibo [16, 17], Green Bank Telescope (GBT) [18], Square Kilometre Array (SKA) [19, 20], Molonglo Observatory Synthesis Telescope (MOST) [21, 22], Canadian Hydrogen Intensity Mapping Experiment (CHIME) [23].

The exploration of these primordial relics may reveal important information about fundamental physics at extremely high energy scales, where one possible class of particle physics models naturally give rise to cosmic strings that are superconducting [24]. These so-called superconducting cosmic strings (SCSs) can be achieved by introducing a charged scalar field whose flux is trapped inside strings with the electromagnetic gauge invariance broken, and hence can yield electromagnetic effects [25]. These primordial relics, if exist in the sky, could behave as giant wires that may release electromagnetic signals in a wide range of frequencies [26–27]. Thus, it is natural to explore the hypothetical possibility for SCSs to explain the observed FRB events, namely, due to the oscillations of string loops [28], dynamics of string cusps and kinks [29–31], and effects of the magnetic field upon string loops [32].

It is interesting to note that, the two parameters of cosmic strings can be strongly constrained by astronomical observations, which are the characteristic tension $\mu$ and current $I_c$ of cosmic strings, respectively. In the Planck’s unit, the string tension is depicted by $G\mu$ with $G$ being the Newton’s constant and the unit of $I_c$ is often scaled in GeV. Namely, the CMB analyses based on the Wilkinson Microwave Anisotropy Probe (WMAP) and the South Pole Telescope can lead to an upper bound on the string tension to be $G\mu < 1.7 \times 10^{-7}$ [33], and this bound was later improved to be $G\mu < 1.3 \times 10^{-7}$ with the data from the Planck satellite [34]. As cosmic strings can also lead to relic gravitational waves in the form of a stochastic background, a model-dependent constraint from the pulsar timing measurements on the string tension can be obtained in about the same order of the bound from CMB [35–40]. Further constraints on SCSs can be derived through the spectral distortions of the CMB photons [41, 42], namely, the parameter region with $10^{-19} < G\mu < 10^{-7}$ and $I > 10^4 \text{ GeV}$ would be ruled out [43].

In this article, with the latest observational developments on the FRB astronomy, we study the updated constraints of the radio transient signals from SCSs. In most of previous works, it has been assumed that all SCSs take the exactly same value of the current, which would greatly simplify the analysis while one could grasp the basic picture of the underlying physics. However, in a much realistic situation, one would expect a probabil-
ity distribution for the currents inside various strings in the Universe. To explore this possibility, we in this article put forward a parametrized model for SCSs, in which the currents are assumed to follow the Poisson distribution. For this type of distribution, the probability of electric neutral strings is the highest, which corresponds to uncharged cosmic strings; while the probability for cosmic strings with larger current becomes lower, which indicates that SCSs can hardly be formed at extremely high energy scales. We argue that, this parametrization can approximately be consistent with the intuition that we have learned from quantum field theory.

The structure of this article is organized as follows. In Sec. II we depict the parametrized model of SCSs and the associated radiation mechanism. Then, in Sec. III we present the numerical estimate based on the newly proposed parametrization and report the updated constraint on the parameter space of these cosmic strings. Sec. IV is devoted to the summary of our results accompanied with a discussion. In the theoretical derivations, we have adopted the natural units with $h = c = 1$. In the numerical calculations, we have followed the setups of the Parkes multi-beam receiver and ASKAP survey. 1

II. CHARACTERISTICS OF COSMIC STRINGS

Cosmic strings could be formed via phase transitions of the very early universe when the manifold of the vacuum background has nontrivial topology for symmetry breaking. The possible probe of these cosmic relics may reveal crucial information about fundamental physics at extremely high energy scales. In particular, these strings could carry a current, i.e. SCSs, which could be achieved by a charged scalar field whose flux is trapped in normal cosmic strings with the electromagnetic gauge invariance broken inside the strings, and hence would give rise to electromagnetic effects. Namely, as described in [31], radiations can be emitted from various structures of SCSs. In the following, we briefly review the radiation mechanism of SCSs and put forward a parametrized distribution function for SCSs.

A. Parametrization of SCSs

Consider a string with the initial length $L_i$ at the initial time $t_i$, its length evolves as:

$$L(t) = L_i - \Gamma_g G\mu(t - t_i),$$  

where $G\mu$ is the dimensionless parameter that characterizes the gravitational interaction of cosmic strings. As cosmic strings produce both gravitational and electromagnetic radiations, the lifetime of a typical string loop can be estimated. The gravitational radiation power takes \[2\]

$$P_g = \Gamma_g G\mu^2,$$

where $\Gamma_g$ is the numerical factor depending on the shape and trajectory of a string loop. Its value typically varies from 50 to 100 [25]. The string lifetime (i.e. loops loses their energy, gradually shrinking and disappears) can be estimated as [25]

$$\tau = \frac{L}{\Gamma G\mu}.$$

Note that, in the literature about the electromagnetic effects of cosmic string, it was assumed that all strings carry the same value of the current. However, this assumption could be relaxed by adopting a probability distribution for the currents inside various strings that may exist in the Universe. Namely, a simple parameterization is to let the currents inside the strings follow the Poisson distribution. Accordingly, we take the event number $dn_{CS}$ for cosmic strings to be exponential distribution of the current, i.e., $\Phi(I)$ times event number of superconducting cosmic strings $dn_{SCS}$, which follows,

$$dn_{CS} = \Phi(I) dn_{SCS} dI,$$

where $I$ has an exponential distribution and $I_c$ can be regarded a free parameter. Moreover, the distribution for $I$ can be expressed as,

$$\Phi(I) = I_c e^{-I/I_c},$$

for $I \geq 0$. We argue that, as these topological defects have formed at different energy scales, the value of the corresponding current inside the strings vary along the relevant energy scales for phase transitions. If $I$ reaches infinity, it corresponds to the ultraviolet limit, but this is unphysical and hence the probability approaches to zero. The factor $I_c$ of the distribution function $\Phi(I)$ is to make the distribution into a normalized function so that the total probability is unity and hence it keeps unitary.

B. Radiations from string loops

The electromagnetic radiation power from SCSs could be enhanced by the radiation power from cusps and kinks, which are estimated as [20 30 31]:

$$P_c^\gamma \sim I^2 (\omega_{max} L)^{1/3} \sim \kappa I \sqrt{\mu},$$

$$P_k^\gamma = \frac{I^2}{\omega} \Psi_{\pm \ln \omega_{max}}/\omega_{min},$$

where superscripts $c$ and $k$ stands for cusps and kinks, respectively. Here $\omega_{max}$ and $\omega_{min}$ denote the highest

1 We refer to \texttt{http://frbcat.org/} for details. Additionally, we have considered two data sets from radio experiments, which are the Parkes multi-beam system and ASKAP with redshift within $z = 2.1$, and 0.84, respectively. All these events acquire extra galactic origin and the flux ranges within a few Jy.
and lowest frequency cutoffs, which are estimated as
\( \omega_{\text{max}} \sim \sqrt{\Omega} \) and \( \omega_{\text{min}} \sim (L/N) \sim 1 \). We assume neither
the numbers of kinks per loop \( N \) nor sharpness of discontinuity \( \Psi \) would induce an order-of-magnitude change
to the radiations from kinks. Typically, \( \kappa \sim O(10) \) is a
pre-factor and \( L \) is the length for the loop.

C. Event Rate of Burst

We want to explore the event rate of radio signals from
string loops under matter dominated epoch. According
to one-scale model for cosmic strings distribution with
the string length \( L(t) \), the number density of string loops
can be expressed in terms of the redshift \( z \) and the length
\( L \) as [25 30],

\[
dn_{\text{SCS}}dI = \frac{C_L(z)(1 + z)^6 \Phi(I)}{P_0^2[(1 + z)^{3/2}L + \Gamma G\mu_0]^2} dLdI , \tag{7}
\]

where

\[
C_L(z) = 1 + \frac{\sqrt{\Theta_m}(1 + z)^{3/4}}{\sqrt{1 + z}^{3/2}L + \Gamma G\mu_0} . \tag{8}
\]

The burst event rate in terms of string loop length \( L \),
redshift \( z \), and kink sharpness \( \Psi \), with the beam width
\( \Theta_w = (L_0)^{-1/3} \) per unit volume is [30],

\[
dN(z, L, I) = \frac{N_p \Theta_w^{-3m}}{L(1 + z)} dn(z, L, I)dV(z) , \tag{9}
\]

we have \( p = 0, m = 2/3 \) for cusps and \( p = 1, m = 1/3 \)
for kinks. In the matter dominated era, the comoving
distance and physical volume are:

\[
r_0(z) = \frac{c}{H_0} \int_0^z \frac{d\xi}{\sqrt{\Omega_m(1 + \xi)^3 + \Omega_A}} , \tag{10}
\]

and

\[
dV(z) = 4\pi \frac{(r_0(z))^2}{(1 + z)^3} dz , \tag{11}
\]

respectively.

Till now, we have demonstrated burst event rate in
terms of loop length and redshift. In the viewpoint of
observable variables, it is quite fascinating to describe
event rate in terms of observable variables like energy
flux per frequency interval and intrinsic duration of the
burst. The burst event rate in terms of observational
parameters then takes the form [30]:

\[
d\dot{N}(z, S, I) = \frac{A}{S} \left[ \frac{v_0 L(S, z, I)}{S} \right]^m f_m(z, S, I)\Phi(I) dzdSdI , \tag{12}
\]

where,

\[
\dot{A} = \frac{AN_p t_0}{(2 - q)} , \tag{13}
\]

\[
L(z, S, I) = \frac{r^2 S\Delta}{T^2 \Psi^2} (v_0(1 + z))^{q/2} \tag{14}
\]

\[
f_m(z, S, I) = \frac{C_L(z)(1 + z)^m - 1/2(\sqrt{1 + z} - 1)^2}{(1 + z)^{3/2}L + \Gamma G\mu_0} , \tag{15}
\]

with \( m = -2/3 \) for cusps and \( m = 1/3 \) for kinks.

A radio signal, all the way from source to receiver,
experiences scattering effect in various ways. For the
observed width \( \Delta \) of FRB signal, we have assumed both
intrinsic and scattering duration caused by cosmological
medium given by [44]

\[
\Delta^2 = \Delta_{\text{ISM}}^2 + \Delta_{\text{IGM}}^2 + \Delta_{\text{int}}^2 , \tag{16}
\]

where \( \Delta_{\text{ISM}} \) and \( \Delta_{\text{IGM}} \) are scattering duration
because of interstellar medium (ISM) and intergalactic
medium (IGM) respectively. Due to ISM, the time broadening
effects (scattering) for radio pulse, are therefore [45]

\[
\log_{10}(\Delta_{\text{ISM}}) = -6.5 + 0.15 \log_{10}(DM_{\text{ISM}}) + 1.1 \log_{10}(DM_{\text{ISM}})^2 - 3.9 \log_{10}(v_0) \tag{17}
\]

where \( DM_{\text{ISM}} \) is a constant equivalent to \( 95\text{pc/cm}^3 \).
Likewise, the rescaling of time broadening effect through
IGM gives [44 49]:

\[
\log_{10}(\Delta_{\text{IGM}}) = -3.0 + \log_{10}(\Delta_{\text{ISM}}) . \tag{18}
\]

To deal with time dilation at observation point for cusps,
one need to consider the cosmological expansion factor.
Therefore, the intrinsic duration at point of observer is
[26 30 31]:

\[
(\Delta_{\text{int}})_{\text{cusp}} \approx \frac{(1 + z) L^{2/3}}{v_e^{1/3}} , \tag{19}
\]

where \( v_e = v_0(1 + z) \) is the speed of the string at
the point of emission near the cusp and \( v_0 \) is the observed
frequency. But, for kinks only the scattering effect will
be considered, i.e

\[
(\Delta_{\text{int}})_{\text{kink}} \approx \frac{1 + z}{v_e} \sim 0 . \tag{20}
\]

The observed FRBs are all from extra-galactic sources.
Assuming a flat FLRW Universe that is dominated by
matter, one finds that the dispersion measure of the IGM is
[47 49]:

\[
DM_{\text{IGM}}(z) = \frac{3cH_0\Omega_b f_{\text{IGM}}}{8\pi Gm_p} \left[ \frac{z^2}{e^{f_{\text{IGM}}(z)}} \right] , \tag{21}
\]

with

\[
e(z) = \frac{\Omega_m(1 + z)^3 + \Omega_A}{\Omega_m(1 + z)^3} , \tag{22}
\]

with \( H_0 \) is the Hubble parameter for today, \( \Omega_b \) be the
baryon mass fraction of the universe and \( f_{\text{IGM}} \) be the
fraction of baryon mass in the intergalactic medium.
At this stage, we have been able to tackle the theoretical predictions of SCSs according to observational data of FRB. In this regard, we can constrain the model parameters very well. There are five parameters in total that describe FRB data accordingly, namely: $G\mu$, $I_c$, $\nu_0$, $\Delta$ and $S$. We are required to fit the event burst rate with the normalized observed data, so for each ($G\mu, I_c$), we need to express event burst rate in terms of redshift. The string current parameter $I$ for cosmic string rely on both the loop length $L$ and the energy scale of the phase transition that was supposed to occur in the very early universe \cite{25}. As a result, we are able to modify a pair ($G\mu, I_c$) according to FRB signals.

As we have considered two parameters for current i.e $I$ and $I_c$, thus, first one is taken to be ($10^{-4}, 10^4$)GeV, based on previous work \cite{31}, and the other one is the parameter space to be chosen to get $\chi^2_{min}$. We need to integrate Equation\cite{12} over respective bandwidth and energy flux for each receiver to get burst event rate for cusps and kinks. For Parkes and ASKAP receiver, using the radiometer equation, the threshold flux is \cite{44} \cite{60},

$$S_x = \frac{SNR \times T_{sys}}{G_{sys} \sqrt{\Delta B N_{pol}}},$$  \hspace{1cm} (23)

where $T_{sys}$ is the temperature of the system, $G_{sys}$ is the system gain, $B$ is bandwidth, $N_{pol}$ is the polarization number and $SNR$ is the signal-to-noise ratio. Following the Table\cite{1} one can get threshold flux for Parkes and ASKAP instrument.

The observational parameters are displayed in Table II. For the event rate for bursts, the contribution of flux has been suppressed outside the given range and is consistent with the detected events\cite{31}. We have few limitations on loop length for cusp. Given the tension of the string, from Eq.\cite{5} we can get the upper bound on L i.e $L < \mu^{3/2}/P\omega_{max}$. Also, for the given $G\mu$, one can expect that the current through strings greater than critical current yields a major contribution in the form of electromagnetic radiations \cite{31}. For statistical analysis, we divide each data set into 6 bins. Make the data normalized so that

$$\sum y_{obs} \Delta z_{bin} = 1 ,$$  \hspace{1cm} (24)

with $y_{obs}$ be the normalized event number per redshift.

To examine the compatibility of theoretical data with the observed ones, we create different values of normalized event burst rate in terms of ($G\mu, I_c$) so that

$$\int y_{th} dz = 1 .$$  \hspace{1cm} (25)

In order to quantify the ability of FRB observations to constrain the parameter space for SCS, we have employed a statistical tool:

$$\chi^2 = \sum_{i} \frac{(y_{obs} - y_{th})^2}{y_{obs}^2} ,$$  \hspace{1cm} (26)

where $n$ be the number of bins. Afterwords, we have determined the burst event rate distribution for two datasets. We are interested in regime with burst event rate per year between $10^5$ to $10^7$.

We have investigated two observational data sets consisting of 25 points from Parkes and 26 from ASKAP. According to our analysis, we have considered 1$\sigma$ confidence level to check the good estimate of parameter space for each experiment. For both instruments, the significance 1$\sigma$ demonstrates the contour with $\chi^2 < 7$. This has been shown in Fig. 1. The red shaded region corresponds to Parkes and the purple contour region for ASKAP. Both allow constrain to parameter space with

### Table I: Specifications of Parkes multibeam and ASKAP

| Parameter      | Parkes       | ASKAP       |
|----------------|--------------|-------------|
| $G_{sys} (K/Jy)$ | 0.69         | 0.029       |
| $B$ (GHz)      | 0.34         | 0.346       |
| $N_{pol}$      | 2            | 2           |
| $T_{sys} (K)$  | 28           | 58          |
| SNR           | 10           | 10          |

### Table II: Observational Parameters

| Parameter      | Parkes       | ASKAP       |
|----------------|--------------|-------------|
| redshift ($z$) | 2.1          | 0.84        |
| $S$ (Jy)       | $[10^{-1}, 10^{-2}]$ | $[10^{-1}, 10^{-2}]$ |
| $\nu_0$ (GHz)  | 1.182, 1.522 | 1.129, 1.465 |

### Table III: Best fits for Parkes and ASKAP with corresponding parameter values, $N$ per year and $\chi_{min}^2$

| Parameter      | Parkes       | ASKAP       |
|----------------|--------------|-------------|
| $G\mu$         | $3.254618 \times 10^{-14}$ | $4.597270 \times 10^{-14}$ |
| $I_c$          | 7.943282     | 3.981072 \times 10^{-14} |
| $\chi_{min}^2$ | 1.09         | 2.31        |
| $N$            | $2.116753 \times 10^7$ | $1.124683 \times 10^4$ |

FIG. 1: $\chi^2$ Distribution with 1$\sigma$ significance: The red shaded region corresponds to Parkes and purple for ASKAP.
We have calculated the burst event rate per year for each observational data set. Results of our analysis is in Fig. 2 displays the findings for our analysis. We have calculated event burst rate per year. Fig. 2 reveals the updated regime, estimated parameter space ranges approximately between $10^3$ to $10^9$ respectively.

The model parameters with corresponding $N$ and $\chi^2_{min}$ are given in Table [I]. The best fitting spot corresponds to $N$ per year for ASKAP data is approximately in line with the analysis done by numerical simulation. But, for Parkes, it might be a bit higher. In order to get an insight into further details, one can refer to [23, 44].

**IV. CONCLUSION AND DISCUSSION**

To summarize, in the present article we have derived the updated constraints on the parameter space for SCS by confronting the theoretically predicted event rate with observational data of FRBs. We have analyzed the observed data from two telescopes, which are the Parkes and ASKAP, respectively.

Note that we have assumed all cosmic strings to be superconducting so that the currents through the string loops follow the Poisson distribution. We proposed a model in which the number density for cosmic strings can be defined in terms of number density for SCS and the distribution of strings’ currents. While reporting results by using Parkes data, we noticed the parameter space suggested by Parkes data for SCS suggested by [31] is slightly broader, demonstrated by Fig. 1.

Another important finding is that, the combination of Parkes and ASKAP constrained the parameter space well enough. Fig. 4 reveals the updated regime, ensured by FRB data from these two radio experiments, is $G\mu \sim [10^{-16}, 10^{-13}]$ and $I_c \sim [10^0, 10^2]$. For each dataset, our detailed analysis declared a best fitting contour estimated by $\chi^2_{min}$. The burst event rate per year for the above mentioned confined parameter space ranges approximately between $10^3$ to $10^9$ which is slightly higher than the analysis conducted by [23, 44]. We suggest that, event number per year could be bit higher due to exponential suppression in the current distribution.

The extant studies have been conducted under some simplifying assumptions, the string tension might be dynamical by considering in terms of current distribution, i.e $G\mu = G\mu \Phi(I)$, we have taken $G\mu$ to be the average tension. Also, we have ignored the cosmological expansion for number density defined in dark energy era. As our universe has been entered into dark energy epoch, it is challenging to probe the radiation mechanism in de sitter universe. The dynamics of strings in an expanding universe described by FLRW metric dominated by matter and dark energy can be explored by considering one-scale model. The lack of convincing theoretical arguments to determine number density in dark energy era has given rise to discrepancy for this approach.

In addition, from all the detected FRBs, six repeated bursts from FRB180814.J0422+73 have been reported [51]. We intend to look at two aspects for repeated bursts, one is observational and the other theoretical. For observational aspect, we expect more data and on theoretical line, we need more in-depth knowledge to explore these signals. In this regard, the precise measurement of

![Figure 2: The burst event rate distribution within 1σ significance contour space: The red shaded region corresponds to Parkes and purple for ASKAP. The lighter to darker shades of each colour corresponds to the regime with $N(\text{yr}^{-1})$ from $10^3$ to $10^9$ respectively.](image)

![Figure 3: In this figure, the normalized observed event rate per redshift from Parkes(red) and ASKAP(orange), and theoretical fitting curve using SCSs model are shown. The observational parameters are listed in Table [II]. The $\chi^2_{min}$ are 1.09 for Parkes and 2.31 for ASKAP. The corresponding parameter values with event rates per year are listed in Table [III].](image)
energy released from our proposed model could help to falsify the theoretical origin for repeated SCSs. Because of the precise constraints by FRBs, SCS might be a theoretical model for FRBs. The current in string loops could be in the range of GeV scale which makes SCS to be a tool to investigate high-energy phenomenon along with collider experiments.

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