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Constraining the Earth-mass Primordial Black Hole Mergers Model of the Non-repeating FRBs Using the First CHIME/FRB Catalog (Post-print)

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Abstract

In this paper, we upgrade the constraints for the Earth-mass primordial black hole mergers model based on the first Canadian Hydrogen Intensity Mapping Experiment (CHIME)/fast radio burst (FRB) catalog. Assuming the null hypothesis that the observed non-repeating FRBs originate from Earth-mass primordial black hole mergers, we find that how the charges were distributed in the primordial black hole population is well described by a double power-law function with typical charge value

Full Text

Preamble

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Abstract

In this paper, we present updated constraints on the Earth-mass primordial black hole merger model based on the first Canadian Hydrogen Intensity Map-

ping Experiment (CHIME) fast radio burst (FRB) catalog. Assuming the null hypothesis that the observed non-repeating FRBs originate from Earth-mass primordial black hole mergers, we find that the charge distribution in the primordial black hole population is well described by a double power-law function with a typical charge value of $q \sim 10$ for $q < q_c$. Here, q represents the charge of the black hole in units of $G^1/2 M$, where M is the mass of the black hole. Furthermore, we infer the local event rate of the bursts to be $8.8 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which indicates that an abundance of the primordial black hole population $f \sim 10^{-4}$ is needed to account for the FRBs observed by CHIME. The results of this paper lay the foundation for further research on the electromagnetic radiation background generated by primordial black hole mergers.

Key words: black hole physics — (stars:) gamma-ray burst: general — (cosmology:) dark matter

1. Introduction

Fast radio bursts (FRBs) are enigmatic astronomical radio transients with observed durations around a millisecond (Lorimer et al. 2007; Cordes & Chatterjee 2019; Petroff et al. 2019). To date, several hundred FRBs have been reported, the majority of which are one-off events, with only dozens of sources identified as repeaters (Cordes & Chatterjee 2019; Petroff et al. 2019; Zhang 2020a, 2023; Xiao et al. 2021). Some studies suggest that the non-repeaters might be intrinsically different from the repeaters (Palaniswamy et al. 2018; Cui et al. 2021; Zhong et al. 2022; Luo et al. 2023; Zhu-Ge et al. 2023). Recently, it has become widely believed that repeating FRBs originate from magnetar activity (Popov & Postnov 2013; Kulkarni et al. 2014; Lyubarsky 2014; Katz 2016; Beloborodov 2017, 2020; Kumar et al. 2017; Metzger et al. 2017, 2019; Wadiasingh & Timokhin 2019; Lu et al. 2020; Lyu et al. 2021) or interactions in binary systems containing at least one compact object (Geng & Huang 2015; Dai et al. 2016; Gu et al. 2016, 2020; Dai 2020; Dai & Zhong 2020; Geng et al. 2020; Ioka & Zhang 2020; Zhang 2020b; Decoene et al. 2021; Deng et al. 2021; Kuerban et al. 2021; Wang et al. 2022; Lan et al. 2023). Due to the very limited observational information on non-repeating bursts, the question of their origin remains mysterious. Although non-repeating FRBs may originate from astrophysical processes such as the collapse of neutron stars into black holes (Falcke & Rezzolla 2014; Zhang 2014; Punsly & Bini 2016) or mergers of two compact stars (Kashiyama et al. 2013; Totani 2013; Mingarelli et al. 2015; Liu et al. 2016; Wang et al. 2016; Zhang 2016; Li et al. 2018; Liu 2018), it is very difficult to explain their extremely high event rates (Deng et al. 2019; Ravi 2019; Meng & Deng 2024).

Given that existing astrophysical models do not perfectly explain non-repeating FRBs, alternative ideas have been proposed. These include oscillations or decay of superconducting cosmic strings (Vachaspati 2008; Cai et al. 2012a, 2012b; Yu

et al. 2014; Zadorozhna 2015; Brandenberger et al. 2017; Ye et al. 2017; Cao & Yu 2018; Imtiaz et al. 2020) and our charged primordial black hole merger model (Deng et al. 2018). According to Deng (2021), mergers of Earth-mass primordial black holes could serve as sources for non-repeating FRBs, potentially explaining all key observational features, particularly the high event rate.

In Deng (2021), we used early FRB samples to constrain the charged Earth-mass primordial black hole merger model. A power-law distribution of charges with a typical charge value $q \sim 10$ was required to explain the data (Deng 2021). These charges may come from the process of accretion of magnetic monopoles in the early Universe (Deng et al. 2018; Wang & Deng 2024). Now a large and uniform FRB sample from the Canadian Hydrogen Intensity Mapping Experiment (CHIME) has been released. In this work, we use the first FRB catalog from CHIME to perform an updated constraint on our model.

2. Sample Selection

Our analyses are based on the large uniform sample from the first CHIME/FRB catalog, which contains 474 non-repeating sources (CHIME/FRB Collaboration et al. 2021). To minimize the impact of selection effects, we exclude some bursts following previous studies (CHIME/FRB Collaboration et al. 2021; Hashimoto et al. 2022; Qiang et al. 2022; Shin et al. 2023): (1) bursts labeled with “excluded-flag = 1”, because they are detected either during pre-commissioning, epochs of low sensitivity, or on days with software upgrades; (2) bursts with signal-to-noise ratio (SNR) < 12 , which can lead to misclassification of FRBs and noise due to perceived differences in visual and system pipeline detection; and (3) bursts with $DM < 1.5 \times \max(DM_{\{YMW16\}}, DM_{\{NE2001\}})$ to ensure that the events come from cosmological distances. After applying all of the above exclusion criteria, 281 non-repeating bursts remain, which constitute the sample used for our analyses.

For those FRBs that did not have redshift measurements, we infer their redshifts from the extragalactic dispersion measures (DMs). Since the host galaxy’s contribution to DM is expected to be small in our model, the host galaxy DM is ignored.¹ Then, the observed DM can be divided into $DM = DM_{\{MW\}} + DM_{\{IGM\}}$, where $DM_{\{MW\}}$ is the contribution from the disk and halo of the Milky Way. We infer the DM from the disk using the electron density model of Yao et al. (2017), and adopt a fixed value of 30 pc cm^{-3} for the DM from the Milky Way halo.

The $DM_{\{IGM\}}$ is the contribution from the intergalactic medium, which is calculated as (Deng & Zhang 2014)

$$DM_{IGM}(z) = \frac{3c\Omega_b f_{IGM} f_e H_0}{8\pi G m_p} \int_0^z \frac{(1+z') dz'}{E(z')}$$

where $\Omega_b = 0.0486$, $f_{\text{IGM}} = 0.83$, $f_e = 7/8$, and $H_0 = 67.74 \text{ km s}^{-1} \text{ Mpc}^{-1}$ are the cosmological parameters. $E(z) = H(z)/H_0$ is the dimensionless Hubble parameter (Planck Collaboration et al. 2016), and m_p is the mass of a proton. When the value of DM subtracts the contribution from the Milky Way, the redshift z can be estimated from the above equation.

Following Deng (2021) and studies on gamma-ray bursts (Bloom et al. 2001; Sun et al. 2015; Zhang 2019), we estimate the isotropic energy of the FRBs within a uniform bandwidth (ν_1, ν_2) in the burst-frame by

$$E_{\text{iso}} = \frac{4\pi D_L^2 F_\nu}{(1+z)^{2-\gamma}} \frac{\nu_2^{1+\gamma} - \nu_1^{1+\gamma}}{(1+\gamma)\nu_c^\gamma}$$

where F_ν is the specific fluence, D_L is the luminosity distance for a given redshift, γ is the spectral index of FRBs, and $\nu_c = 0.6 \text{ GHz}$ is the typical central frequency of CHIME. In this work, we adopt $\gamma = 1.6$ as in Deng (2021). $\nu_1 = 0.4 \text{ GHz}$ and $\nu_2 = 0.8 \text{ GHz}$ are adopted to uniformly correct the energy to the uniform band in the burst-frame.

¹ Nevertheless, we have examined the case for taking a relatively large DM value for the host galaxy, and we found that this did not significantly affect our results.

3. The Method and Results

The model of charged primordial black hole mergers for non-repeating FRBs has been presented in detail by Deng et al. (2018) and Deng (2021). In the context of this model, the peak frequency of the radio bursts is related to the mass of the black holes as $\nu_p \approx 0.6 \text{ GHz}$, and the energy of the bursts is given by $E_{\text{iso}} \approx 10^{39} q \text{ erg}$. Here, q is the charge of the primordial black holes in units of $G^{\frac{1}{2}} M$ as defined in Deng et al. (2018). As in Deng et al. (2018) and Deng (2021), we assume that the charges held by the primordial black holes satisfy an undetermined distribution $f(q)$ for the whole population of primordial black holes.

Since no theoretical information is given about the form of $f(q)$, we simply do not know what the intrinsic distribution of q looks like. Therefore, the intrinsic distribution of q , i.e., $f(q)$, can be derived in a non-parametric way. As we have done in previous works (Deng et al. 2018; Deng 2021), we use the non-parametric method developed by Sun et al. (2015) to derive the intrinsic form of $f(q)$. This method requires the assumption of the redshift distribution of the sources. For our model, the redshift distribution of the sources is theoretically predicted (see Equation (6)), so applying this method to our problem is self-consistent. Let us briefly review this method below.

For a radio telescope survey with fluence threshold F_{th} , field of view Ω , and operational time T , the observed number of FRBs within the range $(q, q + dq)$ is estimated as (Deng et al. 2018; Deng 2021)

$$\frac{dN_{\text{obs}}}{dq} = f(q) \int_0^{z_{\text{max}}(q)} \frac{dR_{\text{PBH}}(z)}{dq} \frac{dV(z)}{dz} dz$$

where $V(z)$ is the comoving volume, and \hat{q} is the charge value needed to account for the energy of the burst (Deng 2021). Also, z_{max} represents the maximum redshift where the FRBs can be detected by a radio telescope with fluence threshold F_{th} . It is calculated by

$$z_{\text{max}}(q) = \min [z_{\text{max}}^{\text{cosmic}}(q), z_{\text{max}}^{\text{survey}}]$$

where $z_{\text{max}}^{\text{cosmic}}$ is determined by requiring $E_{\text{iso}}(q, z) \geq 4\pi D_L^2(z) F_{\text{th}} (1+z)^{\gamma-2}$, and $z_{\text{max}}^{\text{survey}}$ is the maximum redshift covered by the survey.

In the context of our model, the cosmic rate of the sources follows the primordial black hole binary merger rate, which is given by (Ali-Haïmoud et al. 2017; Deng 2021)

$$\frac{dR_{\text{PBH}}(z)}{dq} = \int_0^{t_0} \frac{dR_{\text{PBH}}(z, t)}{dq} dt$$

where t_0 is the age of the Universe at present, and $t(z)$ is the age of the Universe at a given redshift z . The local merger rate n_0 is calculated as (Ali-Haïmoud et al. 2017; Deng 2021)

$$n_0 = \int f(m) \sigma(m) v_{\text{rel}} n_{\text{PBH}}^2 d^3r$$

The form of the function $f(q)$ is taken as (Sun et al. 2015)

$$f(q) = A \left[\left(\frac{q}{q_c} \right)^{-\alpha_1} + \left(\frac{q}{q_c} \right)^{-\alpha_2} \right]^{-1}$$

where $m = M/M_{\odot}$ is the dimensionless mass of primordial black holes, ρ_0 is the density of matter in the present Universe, f represents the proportion of primordial black holes to the matter of the Universe, and $\sigma_{\text{eq}} = 5 \times 10^{-3}$ is adopted for calculation (Deng 2021).

Since the CHIME/FRB sample is large enough, it allows us to make differential distributions and derive the intrinsic differential distribution of q directly from

the observed data. Suppose that ΔN events are detected in a finite bin of q , then from q to $q + \Delta q$, one has (Sun et al. 2015)

$$f(q) \approx \frac{\Delta N(q)}{T\Omega \int_0^{z_{\max}(q)} \frac{dR_{\text{PBH}}(z)}{dq} \frac{dV(z)}{dz} dz}$$

Accordingly, α_1 and α_2 are the power-law indices, and q_c represents the break charge of the distribution. ω defines the sharpness of the break, and $\omega = 3$ is adopted in this work.

Using the Markov Chain Monte Carlo (MCMC) method as in Deng (2021), we obtain the posterior probability distribution of the model parameters: $q_c = 10 \pm 2$, $\alpha_1 = 1.5 \pm 0.3$, and $\alpha_2 = 3.2 \pm 0.5$, at a 1σ confidence level. The fitting results are also displayed in Figures 1 and 2.

Furthermore, based on Equation (8), one can calculate the local event rate $n_{0, > q}$ as a function of q point by point, where q_{\max} is the maximum value in the sample of q . Then one can obtain the local event rate above q_{\min} :

$$R_0 = \int_{q_{\min}}^{q_{\max}} n_{0, > q} dq$$

The result is shown in Figure 1. It is important to note that the black data points in Figure 1 are directly calculated from Equation (8) and represent the intrinsic distribution of q , not the observed distribution. As one can see, $f(q)$ exhibits the characteristics of a broken power law. To describe $f(q)$ analytically, we use a smooth broken power law function to fit it. The form of the function is taken as (Sun et al. 2015)

$$f(q) = A \left[\left(\frac{q}{q_c} \right)^{\omega\alpha_1} + \left(\frac{q}{q_c} \right)^{\omega\alpha_2} \right]^{-1/\omega}$$

where q_{\min} is the minimum value in the sample of q . Here the field of view of CHIME $\Omega/4\pi = 0.3\%$ and the survey time $T = 214.8$ days have been used for calculation (CHIME/FRB Collaboration et al. 2021).

Going back to Equation (7), one can then infer that $f \sim 10^{-4}$ is required to explain the observed number of bursts in the CHIME/FRB sample. Compared to the previous results in Deng (2021), one sees that the inferred values for n_0 are an order of magnitude larger. Moreover, a completely different power exponent is obtained in this work, where it is found that the distribution of q can only be described by a double power-law function, rather than by a simple power-law function as in Deng (2021). The reason for these differences could be that different samples are used.

The results presented above are obtained by using the non-parametric method from the observed energy of the FRBs directly, which focuses primarily on the intrinsic distribution of q , i.e., $f(q)$. In principle, the model should also account for the observed redshifts of the sample, and it would also provide constraints on $f(q)$. To do this, it is necessary to use the method of parameter fitting by assuming a specific form for $f(q)$, so we let this content appear in the Appendix.

4. Conclusions

In this work, we present updated constraints for the Earth-mass primordial black hole merger model based on the first CHIME/FRB catalog. In the context of this model, we derived the charge distribution $f(q)$ in the primordial black hole population directly from the data using a non-parametric method. We find that $f(q)$ is well described by a double power-law function with a typical charge value of $q \approx 10$ for $q < q_c$ and a power-law index $\alpha_1 = 1.5 \pm 0.3$ for $q > q_c$. Furthermore, we infer the local event rate of the bursts to be $8.8 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which indicates that an abundance of the primordial black hole populations $f \approx 10^{-4}$ is needed to account for the FRBs observed by CHIME.

In principle, the primordial black holes could be charged stably by accretion of magnetic monopoles (Wang & Deng 2024), which could result in a charge value up to $q \approx 10^{-4}$ (Deng et al. 2018). This also comfortably explains the energy of FRBs. If this is the case, these charged primordial black holes must have produced a corresponding electromagnetic background when they orbit or merge with each other. This topic will be presented in another paper, based on the results of this work.

Appendix

Similar to Equation (4), the theoretically observed number of sources in the redshift range $(0, z_i)$ can be calculated as (Cao et al. 2018)

$$N_{\text{th}}(z_i) = T\Omega \int_0^{z_i} dz \int_{q_{\text{th}}(z)}^{q_{\text{max}}} f(q) \frac{dR_{\text{PBH}}(z)}{dq} \frac{dV(z)}{dz} dq$$

where $q_{\text{th}}(z)$ is the minimum q where the FRBs at z can be detected by a radio telescope with fluence threshold F_{th} , and it can be calculated according to Equation (5).

To fit the observed redshift distribution, a specific functional form of $f(q)$ is needed. As prior knowledge, we have derived $f(q)$ non-parametrically in the main text and found that it can be described well by Equation (10). Therefore, we adopt Equation (10) as $f(q)$ into Equation (A1) to perform model fitting.

The fitting results are shown in Figures 3 and 4. It can be seen that the parameters of $f(q)$ obtained by fitting the observed redshift distribution here are in good agreement with those obtained in the main text, especially for α_1 and α_2 . However, the fitting value for the local event rate is $n_0 = 25 \pm 8 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which is larger than the value obtained in the main text by a factor of 3 within the error bar. We believe that this difference may be due to differences in methods. In this paper, we tend to adopt the results obtained in the main text because they are derived directly from the data based on the non-parametric approach. Of course, the results obtained here can also be used as a reference.

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