New Insights into the Criteria of Fast Radio Burst in the Light of FRB 20121102A

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ABSTRACT

The total event number of fast radio bursts (FRBs) is accumulating rapidly with the improvement of existing radio telescopes and the completion of new facilities. Especially, the Five-hundred-meter Aperture Spherical radio Telescope (FAST) Collaboration has just reported more than one thousand bursts in a short observing period of 47 days (Li et al. 2021). The interesting bimodal distribution in their work motivates us to revisit the definition of FRBs. In this work, we ascribe the bimodal distribution to two physical kinds of radio bursts, which may have different radiation mechanisms. We propose to use brightness temperature to separate two subtypes. For FRB 20121102A, the critical brightness temperature is $T_{\text{B,cri}} \approx 10^{34}$ K. Bursts with $T_{\text{B}} \geq T_{\text{B,cri}}$ are denoted as “classical” FRBs, and further we find a tight pulse width-fluence relation ($T \propto F_{\nu}^{3.386}$) for them. On the contrary, the other bursts are considered as “atypical” bursts that may originate from a different physical process. We suggest that for each FRB event, a similar dividing line should exist but $T_{\text{B,cri}}$ is not necessarily the same. Its exact value depends on FRB radiation mechanism and properties of the source.

Key words. Methods: statistical – Radiation mechanisms: non-thermal

1. Introduction

Fast radio bursts (FRBs) are new bright millisecond radio pulses that the first discovery was just in 2007 (Lorimer et al. 2007). In early years, doubt exists whether FRBs are astrophysical, until a new sample has been identified in 2013 (Thornton et al. 2013). Ever since then this mysterious phenomenon starts to attract intense attention from the community with breakthroughs coming one after another (for reviews, see Katz 2018; Popov et al. 2018; Petroff et al. 2019; Cordes & Chatterjee 2019; Zhang 2020; Xiao et al. 2021; Petroff et al. 2021). One striking achievement is the discovery of the first repeating event FRB 20121102A in 2016 (Spitler et al. 2016; Scholz et al. 2016) and later the identification of its host galaxy (Chatterjee et al. 2017; Marcote et al. 2017; Tendulkar et al. 2017). Up to now, there are more than twenty repeaters and six hundred apparently non-repeating FRBs in the catalog (Petroff et al. 2016; The CHIME/FRB Collaboration et al. 2021). However, it is still under hot debate whether genuinely non-repeating FRBs exist (Caleb et al. 2018; Palaniswamy et al. 2018; Caleb et al. 2019; Xiao et al. 2021). A few works have discussed the possibility to judge this question using the number fraction of repeaters (Caleb et al. 2019; Lu et al. 2020; Ai et al. 2021; Gardenier et al. 2021). With the accumulation of observing time, this fraction will increase to 100 % if all FRBs repeat. Otherwise, it will peak at a value less than 100 % at a certain time (Ai et al. 2021).

Except for the repeating behavior, currently there is no good criterion for the classification of FRBs yet. Actually, the definition for FRBs is not very strict now. Generally, an FRB is characterized by duration ($T \sim$ millisecond) and extremely high brightness temperature (typically $T_{\text{B}} > 10^{36}$ K). Sometimes a large dispersion measure is needed to distinguish FRBs from rotating radio transients (RRATs). Among all the observational properties, brightness temperature seems the most promising criterion for the classification because it relates to the radiation mechanism directly. Different coherent radio emission mechanisms should have their own “extremes”, resulting in various transient phenomena such as pulsar radio emission, RRATs, giant pulses, nanoshots and so on. They cluster in different regions of the spectral luminosity-duration phase space for radio transients, and the most prominent difference between them is $T_{\text{B}}$ (e.g., Fig. 3 of Nimmo et al. 2021). However, the critical value $T_{\text{B,cri}}$ to define an FRB is not well known. Very recently, the large sample of FRB 20121102A bursts released by the Five-hundred-meter Aperture Spherical radio Telescope (FAST) Collaboration makes it possible to explore this issue (Li et al. 2021).

FRB 20121102A has been well studied before and observed by different radio telescopes (Spitler et al. 2016; Gourdji et al. 2019; Hessels et al. 2019; Rajwade et al. 2020; Cruczes et al. 2021). Its burst rate is very high, thus could be a nice event for studying FRB classification. Previous works showed that the energy distribution can usually be approximated by a power-law form, but the index varies while using different samples from different telescopes (Wang & Yu 2017; Law et al. 2017; Gourdji et al. 2019; Wang & Zhang 2019; Zhang et al. 2021). Similar distributions have been found for solar type III radio bursts (Wang et al. 2021), as well as magnetar bursts (Göğüş et al. 1999; Prieskorn & Kaaret 2012; Wang & Yu 2017; Cheng et al. 2020), which are considered as close relatives to FRBs. However, as the largest single-dish radio telescope now, FAST has a very high sensitivity and the energy threshold for detection is lower than ever. The new sample of FRB 20121102A consists of 1652 bursts and the rate is as...
high as $\sim 122\, \text{hr}^{-1}$. Intriguingly, a bimodal burst energy distribution has been found (Li et al. 2021), indicating that there are two subtypes of FRBs. This motivates us to consider the criterion for FRBs, and we expect to find some empirical relation in the classified subtype sample.

This letter is organized as follows. We introduce the method of classification by brightness temperature and apply it to the FAST sample in Section 2. An evident two-parameter empirical relation is found in Section 3 and we discuss the reasonability of choosing the value of $T_{B,\text{cri}} \approx 10^{33}\, \text{K}$ for FRB 20121102A. We finish with discussion and conclusions in Section 4.

2. FRB classification by brightness temperature

The brightness temperature of an FRB is determined by equaling the observed intensity with blackbody luminosity, which gives

$$T_B = \frac{F_\nu d_A^2}{2\pi k(vT)^2},$$

$$= 1.1 \times 10^{35}\, \text{K} \left(\frac{F_\nu}{\text{Jy}}\right)\left(\frac{\nu}{\text{GHz}}\right)^{-2}\left(\frac{T}{\text{ms}}\right)^{-2}\left(\frac{d_A}{\text{Gpc}}\right)^2,$$

(1)

where $F_\nu$ is flux density, $\nu$ is the emission frequency and $T$ is the pulse width. Note that it should be angular diameter distance $d_A$ here instead of luminosity distance $d_L$ (Zhang 2020; Xiao et al. 2021), therefore the brightness temperatures of FRBs have been overestimated in previous works. Adopting the redshift of $z = 0.19273$ (Tendulkar et al. 2017), we get $d_A = 0.682\, \text{Gpc}$ for FRB 20121102A using the cosmological parameters $H_0 = 67.7\, \text{km}\, \text{s}^{-1}\, \text{Mpc}^{-1}$, $\Omega_m = 0.31$, $\Omega_\Lambda = 0.69$ (Planck Collaboration et al. 2016). With the burst properties given in Supplementary Table 1 of Li et al. (2021), we can easily obtain $T_B$ for each of the 1652 bursts and its distribution is shown in Figure 1. It is obvious that this distribution centers around $\sim 10^{33}\, \text{K}$, lower than the typical $T_B$ of other FRB events. This can be attributed to the ability of detecting low-energy bursts by FAST.

However, the main point we argue is that there is a critical line $T_{B,\text{cri}}$, so the majority of these low-energy bursts may be “atypical”. Bursts with $T_B \geq T_{B,\text{cri}}$ are considered as “classical” FRBs. Since this critical value is unknown, tentatively we choose $T_{B,\text{cri}} = 10^{33}\, \text{K}$ indicated by the plot of spectral luminosity-duration phase space (Keane 2018; Nimmo et al. 2021; Petroff et al. 2021). The influence of choosing different $T_{B,\text{cri}}$ will be discussed later in Section 3. After drawing this dividing line, we find 76 out of 1652 bursts are “classical”. Further the energy distribution for this subtype is shown in Figure 2. Red dashed line represents the probability density function of Gaussian distribution, which has the form $f(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right)$, where $\mu$ is the mean value and $\sigma$ is standard deviation. We can see the energy distribution is consistent with a single Gaussian profile now. Our result is different from another latest analysis of 1652 FAST bursts that suggested a power-law energy distribution for high-energy bursts (Zhang et al. 2021). This may arise from the different method of classification and they used burst energy instead. Till now it might be still not convincing enough to classify FRBs by $T_B$, however, further support can be obtained if we find some similarity within these subtype bursts.

3. A two-parameter relation for “classical” bursts of FRB 20121102A

As we have pointed out, if the subtype of “classical” bursts is true, they should all originate from one particular physical mechanism and have some properties in common. We examine whether a correlation exists between burst width $T$ and fluence $F_\nu$. Intriguingly, while the full FAST sample looks rather scattered on the $T - F_\nu$ plane, we find a tight relation for these 76 “classical” bursts, which is shown in the upper panel of Figure 3. The best-fitting blue line is

$$\log\left(\frac{T}{\text{ms}}\right) = 0.306\log\left(\frac{F_\nu}{\text{Jy}\, \text{ms}}\right) + 0.399.$$  

(2)

We have calculated the correlation coefficient commonly used in linear regression analysis by $r = \sqrt{\frac{\sum (y_\nu - \bar{y})^2}{\sum (y_\nu - \bar{y})^2}}$, where $y_\nu$, $\bar{y}$, $\bar{y}$ are the observed value, regressed value and mean of observed value respectively. The correlation coefficient is $r = 0.936$, very close to unity. Furthermore, an F-test is implemented, where the method of calculating $F_{\text{value}}$ can be found.
in Tu & Wang (2018). We obtain that $F_{\text{value}} = 527.63$ for these 76 bursts, much larger than the critical $F_{\alpha,1.76-2} = 3.97$ where $\alpha = 5\%$ is adopted. Therefore the null hypothesis is rejected and the relation $T \propto F_{\nu}^{-0.306}$ is well established. Since the faint bursts generally have low brightness temperatures (see subsequent Figure 6) and seem to show complex time-frequency structures (Li et al. 2021), we plot the dependence of variance on $T_B$ in the lower panel of Figure 3 but find no clear correlation. Therefore, the morphological changes of the bursts do not have a prominent effect on the $T - T_{\nu}$ relation.

In order to verify this relation, randomly we have analyzed two other samples of FRB 20121102A, i.e., 19 bursts detected by Arecibo and GBT (Hessels et al. 2019) and 36 bursts by Ef-

![Fig. 3. Upper Panel: The scatter plot of pulse width versus fluence for the full FAST sample, in which 76 “classical” bursts are marked with colored dots. The blue solid line represents the best-fitting of $T \propto F_{\nu}^{-0.306}$. The dotted lines represent for different fixed $T_B$ values and the green dashed line is for the critical $10^{33}$ K. Lower Panel: The variance of 76 bursts with respect to the fitting line versus their brightness temperatures. No clear dependence is found.](image1)

![Fig. 4. The scatter plot of pulse width versus fluence for two other samples of FRB 20121102A. Blue dots and line are the same as in Figure 3. Upper panel: 19 bursts from Hessels et al. (2019), marked by stars. Lower Panel: 36 bursts from Cruces et al. (2021), marked by squares. In both panels the red ones are “classical” bursts while the grey ones are “atypical”. Clearly the red ones are consistent with the $T \propto F_{\nu}^{-0.306}$ relation.](image2)

felsberg (Cruces et al. 2021). Different telescopes has different central frequencies and we repeat the above procedure. The results are shown in Figure 4. Red symbols represent bursts with $T_B \geq 10^{33}$ K within these two samples and it is obvious that all these red ones lie fairly close to the best-fitting line. As a comparison, grey dots are those with $T_B < 10^{33}$ K and lie farther away from the line. This greatly increase the confidence of our classification by $T_{B,\text{ crit}}$.

However, one issue remains that we choose $T_{B,\text{ crit}} = 10^{33}$ K somewhat subjectively. Other values of $T_{B,\text{ crit}}$ should also be tested for completeness. We then adopt different values and check whether the $T - T_{\nu}$ relation still holds. We have plotted another two cases of $T_{B,\text{ crit}} = 10^{32.5}, 10^{33.5}$ K in panel(a)(b) of Figure 5 respectively. For relatively low $T_{B,\text{ crit}}$, the scatter is very large and the correlation is loose. Generally, the correlation coefficient $r$ gets larger for stronger correlation between two quan-
ties. We have plotted its evolution with $T_{B,cri}$ in panel(c). Red solid line represent the calculated $r$ and black dashed line represent the critical value of rejection regions. The fact that the red line is above the black one means $T - \mathcal{F}_\nu$ correlation is always expected. Clearly we see that $r$ increases with $T_{B,cri}$, indicating that the relation becomes tighter for higher $T_{B,cri}$. Moreover, we have also plotted the dependence of root mean square (RMS) of fitting residuals on $T_{B,cri}$ in panel(d). The RMS decreases as $T_{B,cri}$ increases. This makes sense since it is easier to pick out real “classical” bursts with higher criterion on $T_B$. Around $10^{33}$ K, this relation is prominent enough and it is reasonable to take this value for FRB 20121102A. Numerical estimation gives the similar value later in Section 4. Note that $T_{B,cri}$ could differ significantly for other FRB events, which will be discussed later.

4. Discussion and Conclusions

This paper has presented a data-oriented research and we have discussed a promising criterion for classifying FRBs, that is the brightness temperature. We have analyzed the FAST sample of FRB 20121102A and found that $T_{B,cri} \sim 10^{33}$ K is a reasonable dividing line. Bursts with $T_B \geq T_{B,cri}$ are “classical” FRBs. For this subtype we have found a tight relation $T \propto \mathcal{F}_\nu^{0.306}$. Further this relation has been verified using different samples.

According to Eq.(1), $T_B$ is roughly in proportion to $\mathcal{F}_\nu^2/T^3$, then we can get a relation $T \sim \mathcal{F}_\nu^{3/10}$ directly for a fixed brightness temperature. However, this simple scaling could not be extended to a sample of bursts with a wide range of $T_B$, as we can clearly see in the upper panel of Figure 3, in which no clear relation exists for the total 1652 FAST bursts. The positive polarization-law relation is hidden because the full sample is a mixture of two types of bursts, and finally emerges if we separate them by $T_{B,cri}$. The width-fluence relation we found is actually for bursts with $T_B$ higher than some critical value, i.e., $T(T_B \geq 10^{33}$ K) $\propto \mathcal{F}_\nu^{0.306}$.

A temporal energy distribution is clear in Figure 1 of Li et al. (2021), favoring the argument that two types of bursts exist. As we can infer from Eq.(1), $T_B \propto E_{FRB}/T^3$. For bursts with higher energy, their brightness temperature is generally higher, as we can see in the trend of Figure 6. The temporal energy distribution actually reflects the rate of two burst types. There are 1576 “atypical” bursts in the FAST sample after our classification. The majority of these bursts should have a different radiation mechanism from “classical” FRBs, for which the brightness temperature could hardly reach $T_{B,cri}$. These bursts could be pulsar radio emission, giant pulses or some other kind of radio emission that have a much higher burst rate than “classical” FRBs. Actually if we plot 1576 bursts on the radio transient phase space, they fill the gap between pulsar radio emission and “atypical” FRBs. Actually if we plot 1576 bursts on the radio transient phase space, they fill the gap between pulsar radio emission and “atypical” FRBs. Alternatively, it is possible that these “atypical” bursts may not belong to a single subtype and consist of different types of radio transient, therefore the correlation between $T$ and $\mathcal{F}_\nu$ is very loose.

The existence of the dividing line should be related to FRB radiation mechanism directly. In principle, the emission frequency, instead of the central frequency of the receiver, should be used to obtain a more physical $T_B$ value. The reason is that some bursts are narrow-banded, for instance, a sample of low-energy bursts from FRB 20121102A are generally detected in less than one-third of the observing bandwidth (Gourdji et al. 2019). Moreover, the pulse width in Eq.(1) should be intrinsic width. Because a physical dividing line, if exist, should be totally intrinsic to the source, and not affected by propagation effect and observation bias. This dividing line is naturally expected, since different types of coherent radio emission have been found to be separated by their brightness temperature in radio transient phase space (Nimmo et al. 2021).

The radiation mechanism of FRBs is largely unknown. Currently, two leading theories are coherent curvature emission by bunched particles in the magnetosphere of a neutron star, and synchrotron maser emission from magnetized shocks outside the magnetosphere (for reviews, see Zhang 2020; Xiao et al. 2021). Constraints can be made using the critical value of brightness temperature. We can rewrite Eq.(1) as

$$kT_B = \frac{\nu F_\nu d_L^2}{2 \pi \nu T^2} \leq \frac{L}{8 \pi \nu^2 T^2}.$$  \hspace{1cm} (3)

Therefor, the FRB luminosity can be estimated as

$$L = 1.09 \times 10^{40} \text{erg s}^{-1} \nu_{15}^3 T_{25}^2 \nu_{303} T_{0.33}.$$  \hspace{1cm} (4)

For the coherent curvature emission mechanism, its luminosity can be expressed as (Zhang 2021)

$$L_{\text{curv}} = N_b N_c^2 \rho \gamma P_{\text{curv}}.$$  \hspace{1cm} (5)

where $N_b$ is the number of bunches, $N_c$ is the number of electrons in one bunch and $\gamma$ is the Lorentz factor of radiating electrons. The radiation power of a single electron is

$$P_{\text{curv}} = \frac{2 \gamma^2 e^2 c}{3 \rho^2} = 4.61 \times 10^{-15} \text{erg s}^{-1} \gamma_{2.5}^3 \rho_{8}^{-2}.$$  \hspace{1cm} (6)

where $\rho$ is the curvature radius. The length of the bunch should be smaller than emission wavelength $\lambda$ in order to be coherent, and the transverse size of causally connection can be approximated as $\sim \gamma \lambda$ (Kumar et al. 2017). Therefore

$$N_c \approx M u_{\text{GJ}} \gamma^2 \lambda^3 = 5.89 \times 10^{17} M_{\gamma}^2 \lambda_{33}^3 \nu_{15}.$$  \hspace{1cm} (7)

where $M$ is the multiplicity factor and the Goldreich-Julian number density is (Goldreich & Julian 1969)

$$n_{\text{GJ}} = \frac{\Omega B}{2\pi e c} = 6.94 \times 10^7 \text{cm}^{-3} B_{15} \nu_{15}^{-1} R_{8}^-.$$  \hspace{1cm} (8)

where we assumed a magnetar engine with surface magnetic field $B_s \sim 10^{15}$ Gauss, rotation period $P \sim 1$ s and emission radius $R \sim 10^6$ cm. Substituting Eq.(6)(7) into Eq.(5), we have

$$L_{\text{curv}} \approx 1.60 \times 10^{31} \text{erg s}^{-1} N_b N_c^2 \gamma_{2.5}^{10} \nu_{303}^2 \rho_{8}^{-2}.$$  \hspace{1cm} (9)

Basically, the Lorentz factor $\gamma$ can not exceed $10^{13}$ due to the drag force exerted by resonant scattering with the soft X-ray radiation field of the magnetar (Beloborodov 2013a). The multiplicity $M \sim 10^2$ from resonant scattering is expected (Beloborodov 2013b). Comparing Eq.(4)(9), we find that in the most optimistic case, the brightness temperature of coherent curvature emission can merely reach $10^{33}$ K. For $T_B > 10^{33}$ K, this model requires unrealistic large value of $N_b N_c^2$, for which the formation and maintenance of the bunches can be problematic (Saggio 1975; Cheng & Ruderman 1977; Kaganovich & Lyubarsky 2010). A more stringent constraint on $T_B$ is given based on a similar method (Lyuikov 2021a). However, this mechanism can still be responsible for “atypical” bursts.

For the maser mechanism from magnetized shocks, a very small fraction of shock energy is released in the form of radio precursor (Hoshino & Arons 1991). Particle-in-cell simulation...
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To conclude, both these two mechanisms have their own limitations. Conservatively speaking, both of them seem unlikely to produce FRBs with $T_B > 10^{33}$ K. So it remains unclear what mechanism makes the “classical” FRBs. There have been tens of possible mechanisms for pulsar radio emission, and it has been proposed that some of them (e.g., free electron laser mechanism) can be applied to FRBs and reach high brightness temperature (Lyutikov 2021b). Interestingly, Zhang (2021) recently suggested that the coherent inverse Compton scattering could be a promising mechanism, in which the bunch formation problem can be largely relieved due to enhanced emission power of a single electron. Plenty of works need to be done to figure out FRB radiation mechanism, and the $T - F$ relation could provide some hints for future studies. Lastly, while we expect a critical brightness temperature for every FRB event, the difference in source property and environment could result in different $T_{\text{B,cri}}$ value. A further analysis on other FRBs using similar method is now in progress.

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Fig. 6. The brightness temperature versus burst energy for the full FAST sample.

References

Ai, S., Gao, H., & Zhang, B. 2021, ApJ, 906, L5
Beloborodov, A. M. 2013a, ApJ, 777, 114
Beloborodov, A. M. 2013b, ApJ, 762, 13
Bochenek, C. D., Ravi, V., Belov, K. V., et al. 2020, Nature, 587, 59
Caleb, M., Spitler, L. G., & Stappers, B. W. 2018, Nature Astronomy, 2, 839
Caleb, M., Stappers, B. W., Rajwade, K., & Flynn, C. 2019, MNRAS, 484, 3816
Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Nature, 541, 58
Cheng, A. F. & Ruderman, M. A. 1977, ApJ, 212, 800
Cheng, Y., Zhang, G. Q., & Wang, F. Y. 2020, MNRAS, 491, 1498
CHIME/FRB Collaboration, Andersen, B. Â. C., Bandura, K. Â. M., et al. 2020, Nature, 587, 54
Cordes, J. M. & Chatterjee, S. 2019, ARA&A, 57, 417
Crucès, M., Spitler, L. G., Scholz, P., et al. 2021, MNRAS, 500, 448
Gardenier, D. W., Connor, L., van Leeuwen, J., Oostrum, L. C., & Petroff, E. 2021, A&A, 647, A30
Goldreich, P. & Julian, W. H. 1969, ApJ, 157, 869
Gouïïu, E., Woods, P. M., Kouveliotou, C., et al. 1999, ApJ, 526, L93
Gouïïu, E., Woods, P. M., Kouveliotou, C., et al. 2000, ApJ, 532, L121
Hessels, J. W. T., Spitler, L. G., Seymour, A. D., et al. 2019, ApJ, 876, L23
Hoshino, M. & Arons, J. 1991, Physics of Fluids B, 3, 818
Kaganovich, A. & Lyubarsky, Y. 2010, ApJ, 721, 1164
Katz, J. I. 2018, Progress in Particle and Nuclear Physics, 103, 1
Keane, E. F. 2018, Nature Astronomy, 2, 865
Kirsten, F., Snelders, M. P., Jenkins, M., et al. 2021, Nature Astronomy, 5, 414
Kumar, P., Lu, W., & Bhattacharya, M. 2017, MNRAS, 468, 2726
Law, C. J., Abruzzo, M. W., Bassa, C. G., et al. 2017, ApJ, 850, 76
Li, D., Wang, P., Zhu, W. W., et al. 2021, Nature, 598, 267
Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777
Lu, W., Beniamini, P., & Kumar, P. 2021, arXiv e-prints, arXiv.2107.04059
Lu, W., Pero, A. L., & Waxman, E. 2020, MNRAS, 498, 1973
Luo, R., Men, Y., Lee, K., et al. 2020, MNRAS, 494, 665
Lyutikov, M. 2021a, arXiv e-prints, arXiv.2107.04414
Lyutikov, M. 2021b, arXiv e-prints, arXiv.2102.07010
Marcote, B., Paragi, Z., Hessels, J. W. T., et al. 2017, ApJ, 834, L8
Metzger, B. D., Margalit, B., & Sironi, L. 2019, MNRAS, 485, 4091
Nimmo, K., Hessels, J. W. T., Kirsten, F., et al. 2021, arXiv e-prints, arXiv:2105.11446
Patalauswamy, D., Li, Y., & Zhang, B. 2018, ApJ, 854, L12
Petroff, E., Barr, E. D., Jameson, A., et al. 2016, PASA, 33, e045
Petroff, E., Hessels, J. W. T., & Lorimer, D. R. 2019, A&A Rev., 27, 4

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