

The Flat Tail in the Burst Energy Distribution of FRB 20240114A (Postprint)

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Abstract

Fast Radio Bursts (FRBs) are enigmatic millisecond-duration radio transients of extragalactic origin, whose underlying mechanisms and progenitors remain poorly understood. FRBs are broadly classified into two categories: repeating FRBs, which emit multiple bursts over time, and one-off FRBs, which are detected as single events. A central question in FRB research is whether these two classes share a common origin. In this study, we present observations of FRB 20240114A, a repeating FRB that entered a hyperactive phase in 2024 January. We conducted a 318 hr monitoring campaign using the Kunming 40-Meter Radio Telescope (KM40M) in the S-band (2.187-2.311 GHz), during which we detected eight radio bursts. We analyzed their properties, including dispersion measure, bandwidth, pulse width, flux, fluence, and energy. Additionally, we searched for counterparts in overlapping data from the Five-hundred-meter Aperture Spherical Telescope (FAST) in the L-band (1.0-1.5 GHz). While no bursts were temporally aligned between the two telescopes, we identified one FAST burst that arrived approximately 6 ms after one of the KM40M bursts. The absence of FAST counterparts for the KM40M bursts suggests that individual bursts from FRB 20240114A are likely narrow-band, with fractional bandwidths less than 10%. By comparing the cumulative event rates from KM40M and FAST observations, we found that the two measurements are compatible, indicating a possible flattening of the event rate at higher energies. This feature aligns with observations of one-off FRBs, supporting the hypothesis that repeating and one-off FRBs may share a common origin.

Full Text

Preamble

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The Flat Tail in the Burst Energy Distribution of FRB 20240114A

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Abstract

Fast Radio Bursts (FRBs) are enigmatic millisecond-duration radio transients of extra-galactic origin, whose underlying mechanisms and progenitors remain poorly understood. FRBs are broadly classified into two categories: repeating FRBs, which emit multiple bursts over time, and one-off FRBs, which are detected as single events. A central question in FRB research is whether these two classes share a common origin. In this study, we present observations of FRB 20240114A, a repeating FRB that entered a hyperactive phase in 2024 January. We conducted a 318 hr monitoring campaign using the Kunming 40-Meter Radio Telescope (KM40M) in the S-band (2.187–2.311 GHz), during which we detected eight radio bursts. We analyzed their properties, including dispersion measure, bandwidth, pulse width, flux, fluence, and energy. Additionally, we searched for counterparts in overlapping data from the Five-hundred-meter Aperture Spherical Telescope (FAST) in the L-band (1.0–1.5 GHz). While no bursts were temporally aligned between the two telescopes, we identified one FAST burst that arrived approximately 6 ms after one of the KM40M bursts. The absence of FAST counterparts for the KM40M bursts suggests that individual bursts from FRB 20240114A are likely narrow-band, with fractional bandwidths less

than 10%. By comparing the cumulative event rates from KM40M and FAST observations, we found that the two measurements are compatible, indicating a possible flattening of the event rate at higher energies. This feature aligns with observations of one-off FRBs, supporting the hypothesis that repeating and one-off FRBs may share a common origin.

Key words: stars: general -stars: magnetars -radio continuum: stars -stars: neutron

1. Introduction

Fast Radio Bursts (FRBs) are a class of astronomical transient phenomena characterized by extremely bright, millisecond-duration radio pulses of extragalactic origin (Zhang 2023). Based on their repeatability, FRBs are classified into two categories: repeating FRBs, which emit multiple bursts over time, and one-off FRBs, which are detected as single events. Since their discovery in 2007 (Lorimer et al. 2007), the number of detected one-off FRBs has grown to approximately 500 (CHIME/FRB Collaboration et al. 2021), largely due to large field-of-view radio sky monitoring programs such as CHIME (Canadian Hydrogen Intensity Mapping Experiment¹⁰) and DSA-2000 (Deep Synoptic Array 2000¹¹). In contrast, the number of known repeating FRBs remains limited to around 60, despite the detection of tens of thousands of individual bursts from these sources (Xu et al. 2022; Zhang et al. 2024). At present, one of the key questions in FRB research is whether repeating and one-off FRBs share a common origin.

The energy distribution of FRBs has been proposed as a critical observational clue to determine whether the two classes share a common origin. Luo et al. (2020a) proposed that one-off FRBs have higher luminosity than that of repeating ones, and Kirsten et al. (2024) examined a large population of bursts from the repeating FRB 20201124A and noted that the burst energy distribution exhibits an extended tail with a shallower power-law index at higher energies. Notably, this phenomenon has also been observed in other active repeating FRBs, such as FRB 20121102A, FRB 20200120E, FRB 20201124A and FRB 20220912A (Kirsten et al. 2024; Konijn et al. 2024; Li et al. 2021; Ould-Boukattine et al. 2024; Pellicciari et al. 2024a; Zhang et al. 2024). These high-energy tails closely resemble the energy distributions observed in non-repeating FRBs, suggesting a possible connection between the two classes.

Observing active repeating FRBs can provide detailed insights into the underlying mechanisms of both repeating and one-off FRBs, shedding light on their potential connections and origins. On 2024 January 26, FRB 20240114A entered an active phase (Shin & CHIME/FRB Collaboration 2024), during which it became hyperactive, emitting bursts at a rate of approximately 500 per hour at a fluence threshold of 15 mJy ms (Zhang et al. 2024). Emission from the source was detected spanning across 0.5-6.0 GHz (Hewitt et al. 2024; Joshi et al. 2024; Limaye & Spitler 2024; Panda et al. 2024; Pellicciari et al. 2024b).

This episode of ultra-high activity provided a unique opportunity to investigate whether the energy distribution of repeating FRBs exhibits an extended tail at higher energies, similar to that observed in one-off FRBs. In this paper, we present observations of FRB 20240114A using the Kunming 40-Meter Radio Telescope (KM40M) at Yunnan Observatories (Hao et al. 2010). Our findings reveal an extended tail in the burst energy distribution, spanning approximately five orders of magnitude. Detailed descriptions of the observations are provided in Section 2, while the data reduction process and analysis of the energy distribution are discussed in Section 3. Finally, broader implications and conclusions are presented in Section 4.

2. Observation

FRB 20240114A was monitored in the S-band (2.187-2.311 GHz) using the KM40M from 2024 March 8 to 2024 November 5, with a total observation time of approximately 318 hr. Additionally, the FRB was observed in the L-band (1.0-1.5 GHz) by the Five-hundred-meter Aperture Spherical Telescope (FAST, Jiang et al. 2019) from 2024 January 28 to 2024 October 29, accumulating a total observation time of 36 hr (see details in J.-S. Zhang et al. 2025, in preparation). The overlapping observation period between KM40M and FAST amounted to approximately 7.2 hr. During these observations, the coordinates of FRB 20240114A were adopted from the European VLBI Network measurements, with R.A. = 21 27 39 .835 and decl. = +04°19 45. 634 (Snelders et al. 2024).

Prior to each KM40M observation, bright pulsars were observed to verify the stability of the observing system. KM40M observations were conducted in search mode using the Roach2-based digital backend, Burst Emission Automatic Roger (BEAR; Men et al. 2019). Data were recorded in 8-bit filterbank format with a time resolution of 17.408 s. The total observation bandwidth of 124 MHz was divided into 127 channels, providing a frequency resolution of 0.98 MHz. In some of our observations, due to interference, we had to observe with only left-handed circular polarization.

The FAST observations were recorded in filterbank format using a ROACH2-based digital backend, with a time resolution of 49.152 s and a frequency resolution of 0.122 MHz. A total of 4096 channels were used to cover the 500 MHz bandwidth. The observation coverage is illustrated in Figure 1 [Figure 1: see original paper].

3.1. Burst Searching and Parameter Measurements

We used the FRB search software BEAR (Men et al. 2019) to perform an off-line search for bursts in the KM40M data. Following the detection of FRB 20240114A by CHIME, which reported a dispersion measure (DM) of 527.7 pc cm⁻³ (Shin & CHIME/FRB Collaboration 2024), we searched for burst signals within a DM range of 522-532 pc cm⁻³ using a step size of 1 pc cm⁻³, which

results in maximal 1% signal-to-noise ratio (S/N) loss for mismatching DM values.

The search employed the matched filter method. The searching grid for pulse width is a geometric series following the equal-signal-to-noise-loss grid approach (Men et al. 2019), where we searched pulse widths ranging from 0.2 ms to 10 ms. We adopted a standard detection threshold of $S/N \geq 7.0$, consistent with practices widely used in the FRB community.

To mitigate radio frequency interference (RFI), we applied a z-dot filter (Men et al. 2019) in the time domain and removed frequency channels with power exceeding the noise floor at the 3σ level. Each FRB candidate identified by the search pipeline underwent visual inspection to exclude signals affected by RFI. Candidates exhibiting narrow-band features or zero-DM interference were discarded. After this process, we identified a total of eight radio bursts. Their pulse profiles, bandpass responses, and dynamic spectra are presented in Figure 2 [Figure 2: see original paper]. We measured the DM, bandwidth, pulse width, flux, fluence, and energy for each burst. These values are summarized in Table 1. Since the methods used to derive these parameters are well-established and widely used, we provide only a brief overview of the techniques. Interested readers are encouraged to refer to the cited literature for more detailed information.

The DM value is measured with two standard techniques, where one can either get the DM by maximizing the burst S/N (Lorimer & Kramer 2012) or by aligning the signal phase gradient in the Fourier domain¹² (Michilli et al. 2018; Xu 2024). The maximum-S/N method is commonly used in the pulsar community. However, this method usually produces a biased estimation for the DM due to the frequency evolution of burst profiles for FRBs (Hessels et al. 2019). In contrast, the Fourier domain phase gradient alignment method was mainly dedicated to FRB signal processing. This method is less affected by the frequency evolution of the profile but tends to yield larger uncertainties. In the current paper, both methods are used in order to cross-check the results. As shown in Table 1, all the DM measurements are consistent with each other and with lower-frequency measurements obtained from FAST data.

In this study, the bandwidth (BW) of the burst signal is measured after the removal of RFI. While a common approach involves fitting a Gaussian function to estimate the bandwidth, this method is not well-suited for the KM40M data. The total system bandwidth of KM40M is approximately 100 MHz, and after RFI mitigation, the usable bandwidth is further reduced. Fitting the bandpass with a Gaussian function often results in bandwidth estimates that significantly exceed the frequency range actually covered by the data. Therefore, in this work, we define the bandwidth as the frequency range over which the burst signal remains detectable after RFI mitigation.

To estimate the pulse width, we employed the Gaussian pulse profile fitting method developed in the 1990s (Kramer et al. 1994). The FRB pulse profile is fitted with multiple Gaussian functions, where the number of components is

incrementally increased until the residuals inside and outside the pulse window exhibit consistent noise properties. Once the parameters of the Gaussian components are determined, the pulse width (W) is defined as the time interval during which the flux exceeds 10% of the peak value. In the pulsar community, this width is commonly referred to as W_{90} , or the full width at a tenth of the maximum.

We estimate the pulse signal flux using the radiometer equation (Lorimer & Kramer 2012):

$$S = \frac{\beta T_{\text{sys}}}{G \sqrt{n_p \tau \text{BW}}} \times \frac{S}{N}$$

where S is the flux in Jy, $\beta \approx 1$ is the digitization factor, $T_{\text{sys}} \simeq 200$ K is the system temperature of the KM40M room-temperature receiver (Hao et al. 2010), $G = 0.27$ K Jy^{-1} is the gain of the radio telescope, BW is the burst bandwidth, τ and n_p are the sampling time and the number of polarization channels, respectively. S/N is the signal-to-noise ratio of the pulse flux, which is estimated by the ratio between the pulse flux and off-pulse noise rms level. There are two primary sources of error in this flux estimation scheme: (1) fluctuations in T_{sys} and (2) the removal of the right-hand circular polarization channel sometimes due to RFI at KM40M. The fluctuation of T_{sys} leads to 20% error in flux, and single left-hand circular polarization observation leads to, on average, 50% underestimation for flux. Thus, the fractional errors of flux-related measurements are 20% and 53% for lower and upper limits, respectively.

The fluence (F) of a radio burst is the time integration of flux (S), i.e., $F = \int S dt$. Under the assumption that the FRB is isotropic, the energy of the burst (Zhang 2023) is:

$$E_{\text{iso}} = \frac{4\pi D_L^2 F}{1+z}$$

where the cosmological redshift and luminosity distance of FRB 20240114A are $z = 0.13$ and $D_L = 603.7$ Mpc (Chen et al. 2025), respectively. In order to compare the pulse energy with different bandwidth, we compute the spectral energy density, which is defined as $E_\nu = E_{\text{iso}}/\text{BW}$.

Using the bursts detected by KM40M, we derived the cumulative event rate as a function of spectral energy density, as shown in Figure 3 [Figure 3: see original paper]. To investigate whether the high-energy tail exhibits a different power-law index, we computed the power-law index for the cumulative event rate by fitting windowed data in spectral energy density. Specifically, we modeled the cumulative event rate as $R(> E_\nu) \propto E_\nu^\alpha$, where α is the power-law index. Since the cumulative distribution is intrinsically correlated, directly fitting for the power-law index is statistically inappropriate. Instead, we adopted the multinomial distribution model (Crawford et al. 1970; James et al. 2019) and

used Bayesian inference to estimate the power-law index and its uncertainty. The software package EMCEE (Foreman-Mackey et al. 2013) was employed to perform the posterior sampling. Our results for the power-law index fitting are also presented in Figure 3. The data window for α spans 0.5 dex in spectral energy density, meaning that the upper boundary of the E_ν window is 3 times the lower boundary (i.e., $\log_{10} 3 \approx 0.5$).

3.2. Concurrent Burst at 1.0-1.5 GHz Observed with FAST

Thousands of bursts from FRB 20240114A have been detected with FAST. The detailed analysis of the FAST data is beyond the scope of this paper and will be published elsewhere (Zhang et al. 2025, in preparation). In this work, we focus on searching for simultaneous bursts in FAST and KM40M data.

We searched for FRBs in the FAST observations overlapping with KM40M observations, totaling 7.2 hr of simultaneous coverage. Similar to the KM40M burst search pipeline, we searched for radio bursts in the overlapping FAST data within a DM range of 522-532 pc cm⁻³ and a step size of 0.1 pc cm⁻³, with a detection threshold of S/N ≥ 7 . Due to the high sensitivity of FAST (16 K Jy⁻¹ (Jiang et al. 2019)), the corresponding flux threshold reaches the mJy level (e.g., 4 mJy for 5 ms duration bursts).

We relied on the time of arrival (TOA) of bursts to identify simultaneous detection in FAST and KM40M data. To compare the TOAs of the radio bursts, we used the software package TEMPO2 (Hobbs et al. 2006) to convert topocentric times to geocentric times, correcting for geometric delays and DM delays. Previously, simultaneous detections of FRB 20190520B have been achieved using dual-telescope observations with Parkes and FAST (Zhu et al. 2024). We tried to search for simultaneous bursts with FAST and KM40M and found no bursts perfectly aligned between FAST and KM40M data; however, we identified a radio burst approximately 6 ms later at FAST than KM40M burst #7.

The temporally aligned dynamic spectra of KM40M burst #7 and the subsequent FAST burst are shown in Figure 4 [Figure 4: see original paper]. Both bursts were dedispersed using the DM values that aligned the signal phase gradient in the Fourier domain, as listed in Table 1.

4. Discussions and Conclusions

It is likely that the individual bursts from FRB 20240114A are rather narrow in bandwidth. We can place an upper limit on the intrinsic bandwidth by examining the KM40M detections in the context of FAST non-detections. For example, burst #7 detected by KM40M reached a flux of 100-200 Jy. Assuming a Gaussian-shaped spectrum, the true burst bandwidth must be less than 220 MHz; otherwise, it would have been detected in FAST data. If a power-law spectrum is assumed (i.e., $S \propto f^\alpha$), the spectral index must be positive and steeper than $\alpha > 17$, which is unlikely. Thus, we conclude that the individual bursts from FRB 20240114A are narrow-band, with a fractional bandwidth (i.e.,

the ratio between bandwidth and central frequency) of less than 10%. The fractional bandwidth of KM40M is only 5%, so, unfortunately, the current KM40M data is not capable of directly testing the bandwidth hypothesis yet.

On the other hand, the spectral density averaged over all bursts from FRB 20240114A may be relatively wide, as indicated by the event rates observed with FAST and KM40M. As shown in Figure 3 [Figure 3: see original paper], the S-band cumulative event rate from KM40M agrees with the L-band results from FAST. If the spectral density of FRB 20240114A evolved significantly from L-band to S-band, we would expect the event rate versus energy density relation to differ markedly. However, there are two caveats to this interpretation. First, the FAST data may be saturated around $E_\nu \sim 10^{31}$ erg Hz⁻¹, meaning the true event rate of KM40M bursts could extend further into the high E_ν regime. Second, the KM40M bursts' population is likely incomplete at the lower end of E_ν (also around $E_\nu \sim 10^{31}$ erg Hz⁻¹), suggesting the true event rate of KM40M bursts could be higher.

Considering these caveats, a larger sample of bursts, ideally from long observations with 100 m class radio telescopes, is needed to confirm these results. We expect that ultra wideband observations (Limaye & Spitler 2024) will provide valuable insights.

We measured the power-law index for the event rate versus energy density relation, as shown in Figure 3 [Figure 3: see original paper]. We noted features similar to those observed in previous studies: the power-law index increases as a function of burst energy for $E_\nu \in [3 \times 10^{28}, 10^{31}]$ erg Hz⁻¹. However, the power-law index appears to drop suddenly to smaller values at $E_\nu \sim 10^{31}$ erg Hz⁻¹, although the statistical significance of this feature is modest (3σ confidence) in our data. Previous investigations of active repeating FRBs (Jahns et al. 2023; Kirsten et al. 2024; Konijn et al. 2024; Ould-Boukattine et al. 2024; Zhang et al. 2024) have reported similar features, suggesting that the flat tail in the event rate at higher burst energies may be a universal characteristic of repeating FRBs.

These rare high-energy bursts may form a population analogous to one-off FRBs, as previously argued. Indeed, when comparing the luminosity density of FRB 20240114A measured with KM40M to other known FRBs and pulsars, the KM40M detections overlap well with one-off FRBs, the majority of sources in the CHIME/FRB Catalog 1, as shown in Figure 5 [Figure 5: see original paper]. Compared to pulsars, another class of celestial objects that emit repeating radio pulses, bursts detected by KM40M further widen the observed gap between FRBs and radio pulsars. The prevailing theories attribute FRB emission to magnetar magnetospheres, supported by substantial observational evidence (Bochenek et al. 2020; CHIME/FRB Collaboration et al. 2020a; Luo et al. 2020b; Xu et al. 2022; Jiang et al. 2024). The extreme flux difference between FRBs and pulsar emissions (spanning 13 orders of magnitude as shown in Figure 5) significantly intensifies the long-standing question of how pulsar-like magnetospheres can repeatably produce such extraordinarily luminous radio

bursts.

It is unlikely that the 6 ms delay for the proximate burst of KM40M burst #7 detected in FAST data is due to a misalignment in burst timing. Both the FAST and KM40M positions are accurate to within 10 m, making it improbable that the 6 ms difference is caused by errors in geometric delay, which would require an implausible 1800 km error in telescope position. Additionally, the BEAR system uses the local network time service, with an error of at most 2 ms, which cannot account for the observed delay. Finally, errors in the DM do not contribute significantly to the 6 ms delay. In this work, we have corrected the time delay between 1.5 GHz (FAST) and 2.187 GHz (KM40M) using the standard dispersion delay formula $\Delta T = 4.15 \text{ ms} \times \text{DM} \times (\nu_1^{-2} - \nu_2^{-2}) \simeq 0.5 \text{ s}$. The DM error for the FAST burst is approximately 0.2 pc cm^{-3} , which introduces, at most, a 0.2 ms error in the time difference between L-band (FAST) and S-band (KM40M). Thus, the significance level of the 6 ms delay between FAST and KM40M burst is 25σ given the DM error. On the other hand, it is possible that the two bursts separated by 6 ms belong to a single burst, with the 6 ms delay representing the time-frequency downward drifting timescale (Hessels et al. 2019). Ultra wideband observations (Limaye & Spitler 2024) will provide further insights into such wideband time-frequency downward drifting phenomena, helping to differentiate between models of drifting mechanisms (Wang et al. 2019; Tuntsov et al. 2021).

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Notes:

¹⁰ <https://www.chime-frb.ca/>

¹¹ <https://www.deepsynoptic.org/>

¹² https://www.github.com/DanieleMichilli/DM_{phase}

Note: Figure translations are in progress. See original paper for figures.

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