Comparative Analysis of the Observational Properties of Fast Radio Bursts at the Frequencies of 111 and 1400 MHz

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Abstract—A comparative analysis of the observational characteristics of fast radio bursts at the frequencies 111 and 1400 MHz is carried out. The distributions of radio bursts by the dispersion measure are constructed. At both frequencies, they are described by a lognormal distribution with the parameters \( \mu = 6.2 \), \( \sigma = 0.7 \). The dependence \( \tau_{sc}(DM) \) of the scattering value on the dispersion measure at 111 MHz and 1400 MHz is also constructed. This dependence is fundamentally different from the dependence for pulsars. A comparative analysis of the relationship between the scattering of pulses and the dispersion measure at 1400 MHz and 111 MHz showed that for both frequencies it has the form \( \tau_{sc}(DM) = DM^k \), where \( k = 0.49 \pm 0.18 \) and \( k = 0.43 \pm 0.15 \) for the frequencies 111 and 1400 MHz, respectively. The obtained dependence is explained within the framework of the assumption of the extragalactic occurrence of fast radio bursts and an almost uniform distribution of matter in intergalactic space. From the dependence \( \tau_{sc}(DM) \), a total estimate of the contribution to the matter of the halo of our and the host galaxy to \( DM \) is obtained \( DM_{halo} + \frac{DM_{host}}{1 + z} = 60 \) pc/cm\(^3\). Based on the \( \log N - \log S \) dependence, the average spectral index of radio bursts is derived \( \alpha = -0.63 \pm 0.20 \), provided that the statistical properties of these samples at 111 and 1400 MHz are the same.

Keywords: fast radio bursts, interstellar medium, intergalactic medium, scattering model

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1. INTRODUCTION

One of the most interesting areas of modern astrophysics is the study of fast radio bursts (FRB), which is a mysterious phenomenon that explains the nature of which catastrophic cosmic events are involved, from mergers of black holes and neutron stars to magnetar flares and asteroid vaporization by a flow of charged particles in the vicinity of pulsars [1–5]. The recent registration of a powerful pulse from the well-known magnetar SGR 1935+2154 [6] with a peak flux density of the order of MegaJansky significantly strengthened the position of supporters of magnetars as sources of FRBs. Nevertheless, in our opinion, this event does not completely cancel out other mechanisms of the occurrence of FRBs.

Until recently, FRBs were recorded sporadically either in archival data or during observations of other space objects, and statistics on them was extremely scarce. The situation has changed with the introduction of special monitoring radio telescopes operating continuously around the clock. Abroad, such tools include, i.e., CHIME [7], ASKAP [8]. There is also such a radio telescope in Russia—the Large Phased Array (LPA) of the Pushchino Radio Astronomy Observatory of the ASC LPI (LPA LPI).

The round-the-clock operation mode and the completeness of the received data of the LPA LPI almost immediately after the launch of the monitoring mode in 2012 led to the idea of trying to register pulse signals of cosmic origin. This idea was first implemented to search for new pulsars [9]. In the fall of 2017, the development of an algorithm for detecting single pulse signals was started. The first results were published in the article by [10]. Further work was developed in the search for FRBs in the direction of two nearby galaxies: M31 and M33. Nine more single pulses were detected, including one repeating pulse. All the events showed no apparent concentration towards the centers of the M31 and M33 galaxies [11]. In order to start making meaningful reliable conclusions about the properties of new pulses, it was necessary to increase their statistics to several dozen, so a search was started for the entire available area of the sky. At the time of writing this article, 63 pulses were detected with the LPA telescope. Although the authors defined them for themselves from the very
beginning as FRBs, it was necessary to study their observational properties and compare them with similar properties of radio bursts observed at other frequencies in order to speak confidently about this. This is the main purpose of writing this article.

Furthermore, we will carry out a comparative analysis of such observational characteristics as the dispersion measure, the dependence of the pulse scattering on the dispersion measure, which, as will be shown later, is fundamentally different from the similar dependence for pulsars, and, finally, the log\(N\) vs.\(\log S\) dependence at the frequencies 111 and 1400 MHz, from which the average spectral index of the pulses will be derived.

The distribution density of the detected radio bursts by the dispersion measure has been studied by many authors. For example, in the work of Cordes et al. [12], the integral distribution density of radio bursts is analyzed in comparison with the spatial distribution of free electrons and radio bursts, and it is concluded that the observed distribution can be explained by a model that includes a dense core and a more rarefied halo. In the work of Dolag et al. [13], the authors conclude that the observed \(DM\) distribution is consistent with the cosmological population at redshifts \(z = 0.6–0.9\), regardless of how the FRBs are distributed with respect to the large-scale structure or properties of the host galaxies.

The scattering of pulses by inhomogeneities of the medium is an important tool for studying the properties of both the interstellar and intergalactic medium. Pulsars are most suitable for the role of pulsed radiation sources for studying the properties of the interstellar medium. The scattering of radio waves by small-scale fluctuations of electron density in the interstellar medium was first recognized as the cause of changes in the radiation intensity of pulsars in [14, 15]. The galactic medium is very heterogeneous, and a detailed study of the processes taking place inside it began almost immediately after the discovery of pulsars. At that time, it was possible to study the interstellar medium at relatively small distances from the observer, since the first recorded pulsars were close objects and had a relatively high flux densities [16–18]. Cordes et al. [19] were the first to propose a two-component model of turbulence in the galactic medium. The first component is understood by the authors as an inhomogeneous medium in the region up to galactic heights \(z < 100 \text{ pc}\), which is associated with the type I population of the Galaxy. The region at a distance of \(\approx 0.5 \text{ kpc}\) is the second component of the model and determines the scattering at high galactic heights \(|b| \approx 10^\circ\). On such scales, the medium, according to the authors, is practically homogeneous. This result turned out to be one of the most important, since it was previously believed that turbulent fluxes are distributed uniformly.

The question related to the mechanism of radiation scattering was considered in more detail by Sutton [20]. It describes in detail all factors leading to multipath propagation of the signal, and also shows the theoretical relationship between the pulse broadening, the decorrelation frequency and the dispersion measure. The paper also considers anomalously strong scattering at small dispersion measures. Such an effect can be observed as a result of the interaction of the pulse with strong turbulent fluxes, i.e., in the HII regions. Also, an example of a strong dependence of scattering on the dispersion measure is given in the work of Bhat et al. [21]. The authors show that for galactic pulsars with the same values of \(DM\), the scattering value can differ by three orders of magnitude.

The main contribution to the scattering of pulses is made by the galactic medium, where the density of matter is significantly higher compared to the intergalactic medium. Accordingly, the scattering of pulses in the galactic medium should depend more strongly on the dispersion measure, which cannot be stated regarding the pulses scattered by the intergalactic medium. This effect was indicated in the works of Lorimer and Karastergiou [22, 23]. It follows from their studies that the scattering of FRB in the intergalactic medium is extremely small or even completely absent, and that pulses recorded at frequencies below \(1 \text{ GHz}\) experience much less broadening, unlike pulses of galactic origin. According to the authors, this makes it possible to observe FRBs at lower frequencies.

In the work of Zhu et al. [24], the authors consider the scattering of FRBs in the intergalactic medium at large cosmological distances, since the average distance to the pulse origin region is \(400–500 \text{ Mpc}\). In the article, it is shown by modeling that the scattering of pulses in the voids is rather weak, but can be amplified by the inhomogeneous distribution of gas in galactic clusters and filaments. In the article [13], Dolag and co-authors model the distribution of intergalactic matter depending on the large-scale structure of the Universe. They also estimate the contribution of the matter of our Galaxy to be approximately two times higher than it was before them, due to the contribution of the Galactic halo at a level of \(DM_{\text{halo}} \approx 30 \text{ pc/cm}^3\).

In contrast to the above-mentioned articles [24] and [13], although we assume that the intergalactic matter is inhomogeneous, the contribution of intergalactic matter scattering can be neglected and considered homogeneous in the first approximation in comparison with the contribution to the scattering of impulses from the matter of our galaxy and possibly the host galaxy.

Returning to the question of scattering at low frequencies, we can cite the work of Kuzmin et al., 2007 [25] as an example. It measured the broadening of pulses from a sample of 100 galactic pulsars at frequencies of 102 and 111 MHz. As a result of the analy-
s, it was found that the dependence of the scattering value on the dispersion measure is described by the power law

$$\tau_{sc}(DM) = 0.06(DM_{100}^{2.2 \pm 0.1}) \text{[s]}.$$  \hspace{1cm} (1)

Kuzmin et al. also showed in [25] that, at a distance of up to 3 kpc, the turbulent fluxes of the scattering medium are statistically homogeneous. But this conclusion was made for the galactic regions. Our work is aimed at studying the effects that occur in the intergalactic environment. Pulsed sources such as radio bursts, which are currently the only means for studying intergalactic propagation effects, are fully suitable for these purposes.

In this work, the scattering value of 63 FRB recorded at a frequency of 111 MHz was studied [10, 11]. The dependence of scattering $\tau_{sc}$ on the dispersion measure $DM$ from Kuzmin’s article [25] is constructed for pulsars with a dispersion measure from 2.97 to 196 pc/cm$^3$. It was decided to supplement this dependence based on measurements of FRB at 111 MHz, the dispersion measure of which is in the range from 172 to 1868 pc/cm$^3$.

The integral distribution of FRB by the peak flux $(\log N - \log S)$ was analyzed in the works of Oppermann, Macquart, and Popov [26–28]. To consider the dependence, pulses registered at frequencies $>700$ MHz were used. Oppermann et al. [26] show that the distribution of pulses by the flux is consistent with a uniform distribution of sources in Euclidean space. In [27], Macquart and Ekers show that the distribution of FRBs in space not only corresponds to the law $S^{-3/2}$, but may also have a steeper dependence. In the article [28], the integral fluence distribution $N(F) = F$ is analyzed and it is shown that the pulses are divided into two populations: $0.5 < F < 3$ Jy ms and $3 < F < 100$ Jy ms. This feature, according to the authors, can be explained either by small statistics or by the effect of selection.

In the following sections, the technical characteristics of the LPA LPI radio telescope are given, the method for measuring the pulse width of FRB is described, and the results obtained are discussed.

2. EQUIPMENT

The observations were carried out with the Large Phased Array (LPA LPI). This is a meridian-type instrument, in which the field of view shows a part of the sky falling from +42.13 to –8.20 degrees in declination. The antenna has a large field of vision, which is ~50 sq. deg. The effective area of the LPA LPI is 47 000 m$^2$ and has a maximum value at the zenith. This value decreases to the horizon proportionally to $\cos z$, where $z$ is the zenith distance. The directional beam (DB) of the LPA LPI is of particular interest. It includes a declination-controlled directional beam (DB-1) and a stationary directional beam (DB-3). Pulsars are observed and studied with DB-1. Round-the-clock monitoring of various sources is carried out with DB-3.

The radio telescope receives radiation in the frequency range $111 \pm 1.25$ MHz. The recording is carried out in two modes using a multi-channel digital receiver. The first mode includes observations with low frequency resolution in six frequency channels of 415 kHz each. In this case, the time resolution is 0.1 s. In the second mode, the recording is carried out in 32 frequency channels, each of which is 78 kHz, and the time resolution is 12.5 ms. Both recording modes are obtained by converting the signal on the FFT processor into 512 channels [29].

The fluctuation sensitivity of the radio telescope in the low-resolution mode is 140 mJy, which makes the instrument one of the best in the world. The self-noise temperature in the system is in the range from 550 to 3500 K and depends on the sky background.

During the observations at the LPA for the period from 2012 to the present, a huge amount of data has been accumulated. As a result of careful processing of data obtained over eight years in daily observations of several sections of the sky with a total area of 310 square degrees, more than sixty new radio bursts were detected. Currently, the search continues throughout the entire area of the sky available for observation.

3. CATALOG “PRAO FRBs at 111 MHz”

In the work of Fedorova and Rodin [11], it was shown that the average rate of registration of bursts by the LPA LPI radio telescope at a frequency of 111 MHz is ~2000 pulses/year. At the beginning of 2021, the archival data of 2018 was processed from January to June in the sky area $\alpha = 11^h 45^m – 12^h 45^m$ and $\delta = 21.38^\circ – 41.72^\circ$. During this period, 51 new phenomena were detected, which, in terms of the entire sky for the year, corresponds to the number of $10^5$ pulses/day and corresponds to the estimates given in various studies [31]. Due to the fact that the number of detected pulses exceeded several dozen, a separate catalog of radio bursts registered at 111 MHz was created—“PRAO FRBs at 111 MHz”.¹ This resource is freely available and includes the following parameters:

1. FRB_name—the name of the pulse. It is given in the form of FRB yymmd.Jra+dec [7].
2. RA, DEC—the pulse coordinates are given in the format RA(J2000) hh:mm:ss, DEC (J2000) deg. The estimate of the error in determining the right ascension is $\pm 2^\prime\prime$, this value of the declination corresponds to $\pm 15^\prime$.

¹ https://www.frb.su/catalogue-prao-frb

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3. GL, GB—the galactic coordinates for the epoch J2000.
4. Date—the date in the yyyy/mm/dd format corresponds to the date in the archive data of the moment when the pulse was detected.
5. UTC_time—the UTC value in the format hh:mm:ss.
6. Flux—the value of the peak flux of FRB (Jy). The accuracy estimate is ±0.05 Jy.
7. DM—the value of the dispersion measure (pc/cm³). The error estimate is ±5 pc/cm³.
8. S/N—the value of the signal-to-noise ratio. For the previously detected impulses from [10, 11], the S/N value was recalculated to a more conservative side.
9. Width_observed—the width of the total pulse after convolution with the template (ms). The measurement error is ±100 ms.
10. Width_original—the initial width of the scattered pulse received by the antenna (ms). The error is ±100 ms.
11. Fluence—the energy density of a fast radio burst (Jy ms).
12. z_YMW16—the value of the redshift z in accordance with the YMW16 electron-density model [32]. This value is only an estimate, since it depends on the accepted value of the average density in the intergalactic medium.

The completeness of the catalog was evaluated by analyzing the difference between the histogram of the distribution by DM and the lognormal distribution (see Fig. 7 below). The histogram shows that there is a shortage of pulses at DM < 200 and DM > 700. The deficit is a fraction ~0.32 of the total distribution area. This value is close to the proportion of discarded pulses ~43% that were rejected due to strict selection criteria: if the pulse was not visible in all six channels, then it was not included in the catalog, although it was most likely a real pulse. Thus, according to our estimates, the catalog of radio bursts at 111 MHz is full at ~60–70%.

Below, for each pulse, there is a dynamic spectrum in six frequency channels (upper image) and a profile (lower image). The pulse amplitude is given in ADC units, the countdown is understood as a unit of time equal to 0.1 s.

4. DATA PROCESSING

The method of isolating single pulse signals is described in detail in previous articles by Fedorova and Rodin [10, 11], so we will focus on it briefly. Since the LPA antenna receives a signal scattered on the inhomogeneities of the cosmic plasma, and the signal undergoes additional broadening when received in the frequency band, a convolution with a template of a consistent shape (an exponentially decaying pulse) is used to isolate it. In radiophysics, this approach is called a correlation receiver, and the result of convolution of a signal with a template is a signal function. Since the typical values of the dispersion measures of the detected FRB are several hundred pc/cm³, it was decided to use a template with a characteristic width $t_s = 1$ s, which according to formula (1) corresponds to the dispersion measure $DM = 360$ pc/cm³. As was shown in the work of the authors [10], such a correlation approach can significantly improve the signal-to-noise ratio of the detected signal, as well as improve the level of fluctuation sensitivity up to 44 mJy. The article [11] shows an example of recording before and after using a convolution with a template, where it is clearly visible that it is not possible to detect a pulse signal without using a correlation receiver.

In this article, we consider the broadening of the pulse due to scattering, so we will further describe the procedure for measuring the width of the radio burst. Analytically, the shape of the template $p(t)$ and the scattered pulse $s(t)$ is written as

$$ (p(t), s(t)) = (a, b) \left\{ \begin{array}{ll}
1 - \exp(-t/t_s), & 0 \leq t \leq \tau, \\
\exp(-t/t_s)(\exp(-t/t_s) - 1), & 0 \leq \tau \leq t,
\end{array} \right. \quad (2) $$

where $a, b$ are the amplitudes of the template and the pulse, respectively, $t_s$ is the scattering of the pulse, $\tau$ is the broadening of the pulse in the frequency channel. For the template, as already mentioned earlier, the value $t_s = 1$ s. It is also necessary to require the fulfillment of the condition $\int_0^\infty p(t) = 1$ for the conservation of the pulse energy. The shapes of template and pulse are shown in Fig. 1.

The signal function is a convolution of the noisy signal $s(t)$ and the template $p(t)$:

$$ f(t) = \int_{-\infty}^\infty p(t)s(t-t_s)dt_s. \quad (3) $$

Its graph is shown in Fig. 2.

Since the shape of the signal function is strongly distorted by the influence of noise, the practical approach used Gaussian fitting to measure the pulse width, and the asymmetry of the pulse was not considered. The position of the pulse was determined by the position of the maximum in the recording, the pulse amplitude was reduced to one. Thus, the only parameter to be determined was the pulse width $\sigma$. Since the Gaussian parameter $\sigma$ is determined at the height $1/\sqrt{e}$, and the scattering value is measured at the height $1/e$, the scattering of the pulse received by the antenna...
was calculated using the formula $\tau_{sc} = 2\sqrt{2}\sigma - \tau - t_s$, where $\tau$ is the broadening in one frequency channel, and $t_s = 1$ s is the characteristic width used for smoothing the template.

5. RESULTS

The results of measurements of the scattering value of 63 pulses, as well as some parameters of FRB from the catalog “PRAO FRBs at 111 MHz”, are presented.
Fig. 3. Dependence of the broadening of pulsar pulses and radio bursts due to scattering on the dispersion measure $\tau_{sc}(DM)$. The black circles show measurements at 111 MHz for pulsars. The gray diamonds show measurements at 111 MHz for fast radio bursts.

Fig. 4. Dependence of the broadening of radio burst pulses due to scattering on the dispersion measure at 1.4 GHz according to the FRB catalog.

in Table 1. It contains the names of twelve previously detected pulses [10, 11] and 51 new ones. If the pulses were recorded on the same day, but in different beams of the radiation pattern of the LPA LPI radio telescope, then the coordinates were added to the standard form of the name of the phenomenon. The coordinates of each pulse for the epoch J2000 are given in the second column of Table 1. The third column con-
### Table 1. Parameters of fast radio bursts recorded at a frequency of 111 MHz

| FRB                | Coordinates, \( \alpha, \delta \) | \( DM, \) pc/cm\(^3\) | Scattering value, ms | Fluence, Jy ms | S/N |
|--------------------|-----------------------------------|---------------------|---------------------|----------------|-----|
| FRB121029          | 00:12:00 +42.06                   | 732                 | 321                 | 442            | 4.3 |
| FRB141216          | 00:14:00 +41.64                   | 545                 | 869                 | 752            | 3.6 |
| FRB131030          | 00:25:00 +39.98                   | 207                 | 526                 | 494            | 6.9 |
| FRB180321          | 00:33:00 +42.03                   | 596                 | 1634                | 2326           | 5.3 |
| FRB160206          | 01:01:00 +41.63                   | 1262                | 1594                | 1506           | 5.6 |
| FRB140212          | 01:31:00 +30.54                   | 910                 | 389                 | 973            | 3.6 |
| FRB151125.1        | 01:13:00 +30.98                   | 273                 | 1679                | 1856           | 3.3 |
| FRB151125.2        | 01:32:00 +30.98                   | 273                 | 1466                | 1671           | 5.3 |
| FRB151018          | 05:21:00 +33.1                    | 570                 | 494                 | 3500           | 5.9 |
| FRB160920          | 05:34:00 +41.75                   | 1767                | 423                 | 1100           | 3.3 |
| FRB170606          | 05:34:00 +41.75                   | 247                 | 100                 | 1782           | 3.0 |
| FRB180606          | 11:43:58 +25.08                   | 331                 | 492                 | 445            | 7.0 |
| FRB180622          | 11:46:06 +37.01                   | 222                 | 315                 | 603            | 6.0 |
| FRB180417          | 11:47:06 +24.6                    | 515                 | 481                 | 757            | 6.3 |
| FRB180614          | 11:48:35 +27.34                   | 577                 | 520                 | 757            | 5.3 |
| FRB180616          | 11:48:48 +39.13                   | 576                 | 415                 | 723            | 5.8 |
| FRB180426          | 11:49:01 +35.30                   | 362                 | 574                 | 551            | 6.5 |
| FRB180607          | 11:49:54 +30.96                   | 438                 | 314                 | 512            | 7.0 |
| FRB180427          | 11:52:07 +26.91                   | 305                 | 471                 | 586            | 6.7 |
| FRB180423          | 11:53:20 +30.51                   | 385                 | 387                 | 475            | 6.4 |
| FRB180603          | 11:56:29 +22.71                   | 1865                | 1281                | 1627           | 5.9 |
| FRB180417.J1155+4112 | 11:55:27 +41.21                   | 273                 | 866                 | 590            | 5.7 |
| FRB180627          | 11:55:58 +38.69                   | 1740                | 1205                | 2456           | 7.0 |
| FRB180513          | 11:58:41 +28.27                   | 750                 | 947                 | 620            | 5.0 |
| FRB180502          | 11:58:57 +23.66                   | 570                 | 533                 | 690            | 5.3 |
| FRB180428          | 11:59:14 +26.50                   | 375                 | 358                 | 534            | 9.5 |
| FRB180428.J1200+4136 | 12:00:13 +41.61                   | 198                 | 134                 | 476            | 6.2 |
| FRB180629          | 12:01:20 +26.50                   | 307                 | 280                 | 352            | 6.5 |
| FRB180507          | 12:03:18 +41.62                   | 625                 | 792                 | 985            | 6.9 |
| FRB180429          | 12:03:32 +40.79                   | 348                 | 503                 | 551            | 7.3 |
| FRB180502.J1207+3726 | 12:07:07 +40.79                   | 1373                | 2612                | 2292           | 6.5 |
| FRB180625          | 12:07:23 +33.59                   | 245                 | 190                 | 273            | 6.3 |
Table 1. (Contd.)

| FRB              | Coordinates, $\alpha$, $\delta$ | $DM$, pc/cm$^3$ | Scattering value, ms | Fluence, Jy ms | S/N |
|------------------|----------------------------------|-----------------|----------------------|---------------|-----|
| FRB180628        | 12:08:20 +22.71                  | 300             | 302                  | 414           | 6.4 |
| FRB180609        | 12:08:56 +29.19                  | 324             | 269                  | 357           | 6.9 |
| FRB180616.J1210+2722 | 12:10:50 +27.37               | 560             | 642                  | 654           | 6.6 |
| FRB180617        | 12:11:25 +34.02                  | 575             | 453                  | 586           | 6.2 |
| FRB180521        | 12:12:10 +27.82                  | 214             | 255                  | 487           | 6.1 |
| FRB180507.J1212+2116 | 12:12:19 +21.28               | 560             | 256                  | 916           | 6.6 |
| FRB180502.J1216+3750 | 12:16:51 +37.85                | 638             | 528                  | 729           | 8.5 |
| FRB180503        | 12:18:42 +27.30                  | 242             | 561                  | 633           | 7.0 |
| FRB180531.J1221+3751 | 12:21:26 +37.85                | 465             | 519                  | 679           | 4.9 |
| FRB180603.J1223+3726 | 12:23:11 +37.44               | 1680            | 1165                 | 1037          | 4.3 |
| FRB180504        | 12:25:51 +41.21                  | 670             | 626                  | 502           | 5.0 |
| FRB180514        | 12:26:59 +34.44                  | 288             | 305                  | 348           | 5.6 |
| FRB180604        | 12:27:08 +32.28                  | 219             | 632                  | 403           | 5.9 |
| FRB180522        | 12:27:43 +26.91                  | 578             | 217                  | 432           | 6.2 |
| FRB180504.J1228+2844 | 12:28:19 +28.74               | 439             | 764                  | 463           | 6.3 |
| FRB180521.J1228+4112 | 12:28:49 +41.21               | 279             | 220                  | 290           | 7.0 |
| FRB180516        | 12:29:19 +38.70                  | 170             | 184                  | 389           | 6.0 |
| FRB180509.J1229+3030 | 12:29:37 +30.50                | 231             | 744                  | 491           | 5.8 |
| FRB180605        | 12:29:47 +29.19                  | 227             | 560                  | 536           | 11.5|
| FRB180609.J1230+2627 | 12:30:19 +26.46               | 420             | 913                  | 1018          | 8.0 |
| FRB180607.J1231+2911 | 12:31:20 +29.19               | 350             | 431                  | 583           | 6.8 |
| FRB180610        | 12:31:46 +41.21                  | 175             | 508                  | 372           | 5.7 |
| FRB180531        | 12:31:56 +38.28                  | 310             | 786                  | 723           | 7.5 |
| FRB180615        | 12:37:05 +38.70                  | 450             | 597                  | 633           | 6.2 |
| FRB180504.J1243+3635 | 12:43:05 +36.59               | 608             | 793                  | 872           | 4.3 |
| FRB180511        | 12:43:07 +26.46                  | 1049            | 1234                 | 1282          | 7.0 |
| FRB180620        | 12:43:42 +41.62                  | 155             | 121                  | 349           | 7.0 |
| FRB180504.J1244+3518 | 12:44:11 +35.30               | 298             | 293                  | 329           | 6.0 |
| FRB180620.J1245+3124 | 12:45:49 +31.40               | 409             | 244                  | 459           | 5.1 |
| FRB180601        | 12:48:59 +24.13                  | 403             | 311                  | 704           | 6.5 |
| FRB161202        | 23:44:00 +40.80                  | 291             | 808                  | 705           | 4.2 |
contains the dispersion measure of radio bursts, measured with an accuracy of $\pm 5$ pc cm$^{-3}$. The last column of the table contains the value of the pulse scattering $\tau_{sc}$.

A comparison of the two $DM$ distributions at 111 and 1400 MHz showed that both of them are described by the lognormal distribution

$$P(x) = \frac{\mu}{x \sqrt{2\pi\sigma^2}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$

with the parameters $\mu = 6.1-6.2$, $\sigma = 0.7$ and, thus, at a statistically significant level, they coincide and correspond to the range of characteristic values $DM = 252-954$ pc cm$^{-3}$. In some papers, the authors derive distributions by subtracting the contribution of the Galaxy $DM_{MW}$ from the total $DM$. In this paper, we use the full value of $DM$, since $DM_{MW}$ is often known with a relative accuracy of 0.5 and, thus, its exclusion introduces an additional error in the distribution.

Based on the data of Table 1, a graph of the dependence of the scattering value $\tau_{sc}$ on the dispersion measure $DM$ was constructed together with the dependence for pulsars given in the article [25]. This graph is shown in Fig. 3.
For FRBs, the power dependence is weaker in comparison with the dependence for pulsars: if for pulsars observed at a frequency of 111 MHz, the authors [25] determine the slope coefficient $k = 2.2 \pm 0.1$ (formula (1)), then for FRBs recorded also at a frequency of 111 MHz, we give the formula

$$\tau_{sc}(DM) = 20.2DM^{0.49\pm0.18} \text{ ms}.$$  

The dependence $\tau_{sc}(DM)$ was also constructed for FRBs at a frequency of 1.4 GHz from the FRB catalog [30]. The graph of this dependence is shown in Fig. 4. To construct the dependence, 59 pulses with a scattering value from 0.34 to 24.3 ms and a dispersion measure from 114 to 2596 pc cm$^{-3}$ were used. In this case, the dependence of scattering on $DM$ is described by the formula $\tau_{sc} = 0.176DM^{0.43\pm0.15}$ ms. The slope coefficient $k = 0.43 \pm 0.15$ within the error is consistent with the result obtained for radio bursts at 111 MHz.
Figure 5 shows a graph of the \( \log N - \log S \) dependence, built at different frequencies. If we assume that the observed samples have the same properties, then the average spectral index of radio bursts \( \alpha = -0.63 \pm 0.20 \) can be derived from the mutual shift of the graphs.

By analogy with pulsars, a low-frequency break caused by absorption on free electrons or radiation features should be observed in the spectra of radio bursts, then it is possible to calculate the break frequency \( f_1 \) assuming several spectral indices at a frequency of 1400 MHz and a flat spectrum in the low-frequency region, which is shown in Table 2.

### Table 2. Break frequency \( f_1 \) at different spectral indices \( \alpha \)

| \( \alpha \) | \( f_1 \), MHz |
|---|---|
| -1 | 130 |
| -1.3 | 230 |
| -1.7 | 350 |

**6. DISCUSSION**

The obtained power dependence \( \tau_{sc}(DM) \) at a frequency of 111 MHz turned out to be weaker in comparison with \( \tau_{sc}(DM) \) for pulsars (the exponent \( k \sim 0.5 \) instead of \( k \sim 2 \)). The exponent \( k \) within the error is consistent with the exponent \( k \) of the dependence \( \tau_{sc}(DM) \) constructed for a sample of FRB at a frequency of 1.4 GHz from the FRB catalog [30].

Other authors have already considered the scattering of FRB on inhomogeneities of the intergalactic plasma. For example, we can cite the work by Zhu et al. [33], where the authors modeled scattering by setting different sizes of inhomogeneities along the line of sight. They obtained a dependence \( \tau_{IGM} \sim DM_{IGM}^{0.5} \) that does not explain the experimental power law \( \tau \sim DM^{0.5} \), although it fits into the spread of data on the graph \( \tau \sim DM \).

In our work, we explain the obtained relationship within the framework of the idea in which the pulse is scattered along the entire line of sight, but the main scattering occurs in the host and our galaxy, and the intergalactic medium on the propagation path is sparse and does not have a dominant influence on the...
magnitude of the scattering of pulses despite large values of $DM$. Once again, we emphasize that we do not cancel scattering in the intergalactic environment, but neglect it. The magnitude of the exponent $k$ in the experimental dependence $\tau_{sc}(DM)$ is determined by the position of the scattering screen along the “source—observer” line. We associate the position of the scattering screen with the boundary of our galaxy or the host galaxy, where the direction of propagation of the pulse deviates from the initial one. A classic example of the model of scattering of a pulse signal on a thin screen can be found in the article by Scheuer

![Graphs showing the dependence of pulse shape on the number of screens](image)

**Fig. 9.** Dependence of the pulse shape of a fast radio burst on the number of scattering screens on the line of sight.

### Table 3. Observational parameters of the conducted surveys and special observations of fast radio bursts

| Telescope | Frequency of obs., MHz | Band, MHz | Sampling interval $\tau_s$, s | $T_{\text{obs}}$, h. of search | Area, sq. deg | $S_{\beta}$, Jy | Article | Note |
|-----------|------------------------|----------|------------------------------|-------------------------------|-------------|-------------|---------|------|
| MWA       | 170–200                | 1.28 × 24 | 0.5                          | ?                             | 450         | 0.84, 4.57, 6.64 | Sokolowski, 2018 [36] | Sensitivity for different sources |
| MWA       | 139–170                | 1.28 × 24 | 2                            | 10.5                          | 400         | 0.35        | Tingay, 2015 [37]    |
| LOFAR (UK) | 145                   | 6        | 0.005                        | 1445                          | 4193        | 62          | Karastergiou, 2015 [23] |
| LOFAR     | 110–190                | 80       | 0.05                         | 2 × 0.67                      | —           | 2           | Chawla, 2020 [38]    | FRB180916.J0158+65 |
| LOFAR     | 110–188                | 78       | 0.004                        | 18.3                          | 0.007       | 10          | Houben, 2019 [39]    | FRB121102 |
| LPA       | 111                    | 2.5      | 1                            | 49910                         | 310         | 0.044       | Fedorova, Rodin, 2019 [10, 11] | 0.14 Jy/$\sqrt{10}$ |
With this approach, since we are dealing with a substance on the line of sight in the study of dependence, it is convenient to measure the distance in units of $\tau_{sc}(DM)$. Obviously, since the concentration of matter $n_e$ in the galactic and intergalactic medium differs significantly, the dependence $DM(L)$ will not be linear.

\[ DM = \int_0^L n_e dl. \]

We divide the measured dispersion measure $DM$ of the radio burst into the following components:

\[ DM = DM_{MW} + DM_{halo} + DM_{EG} + \frac{DM_{host}}{1 + z}, \]  

where $DM_{MW}$ is the contribution of the Galaxy’s matter, which is modeled based on observations of pulsars.

Fig. 10. Dynamic spectra and profiles of pulses.
The remaining amount $DM_{\text{halo}} + DM_{\text{EG}} + \frac{DM_{\text{host}}}{1+z}$ is the contribution $DM_{\text{halo}}$ of the matter of the halo of our Galaxy, $DM_{\text{EG}}$ is the contribution of extragalactic matter, $\frac{DM_{\text{host}}}{1+z}$ is the contribution of the matter of the host galaxy, and $z$ is its redshift. Of all these quantities, only $DM$ and $DM_{\text{MW}}$ are well known. For the halo, as mentioned earlier, an estimate of $DM_{\text{halo}} \approx 30 \text{ pc cm}^{-3}$ is known.

Figure 6 shows the scheme of signal propagation from the source to the observer. The point $C$ indicates the area of occurrence of a fast radio burst, and the point $A$ is the observer. The curved line in the diagram...
shows a thin scattering screen. $R$ and $r$ are the distance from the observer to the scattering screen and from the screen to the point of origin of the pulse, respectively.

From the point $C$, the pulse propagates towards the observer, then falls on the scattering screen, which deflects the pulse by an angle $\delta$, and falls to the observer. In this case, the phase lag $\Delta$, which we associate with the scattering $\tau_{\text{sc}}$ and the shape of the pulse, is defined as

$$\Delta = AB + BC - AC = K \frac{\delta^3}{2} R \left(1 + \frac{R}{r + R}\right),$$  

(6)
where $\delta = \alpha + \beta$. In accordance with the use of quantities $DM$ as a characteristic of distance in formula (5), the observed $DM \equiv r + R$ is responsible for the distance $r + R$, $DM_{MW} + DM_{halo} + \frac{DM_{host}}{1 + z} \equiv R$ is responsible for $R$, and $DM_{MW} \equiv r$ is responsible for $r$.

Expression (6) is symmetric with respect to the variables $r$ and $R$. Therefore, for simplicity, one screen can be considered during modeling.

As part of the work, simulation was carried out, which, as mentioned above, consisted in changing the position of the screen along the line of sight. The distance $r + R$ to radio bursts was set in accordance with
the experimental distribution $DM$ of all registered radio bursts, which is shown in Fig. 7.

The deviation angle $\delta$ was set as a normally distributed value with an average of 0 and $\sigma = 10^{-3}$ rad, which corresponds in order to the observational data of pulsar scattering. The value $K$ was selected experimentally so that the scattering value $\tau_{sc}$ at the given $DM$ and $\delta$ corresponds to the observed one. The distance $R$ was determined by a lognormal distribution with parameters $\mu = 2.7$ and $\sigma = 0.3$ corresponding to the model distribution $DM_{MW}$ in our Galaxy [32, 34] taken from the FRB catalog. The simulation results are shown in Fig. 8. The experimental coefficient $k \approx 0.5$ of the dependence $\tau_{sc} \sim DM^k$ corresponds to
the contribution to $DM$ of the host and our Galaxy at the level of $DM_{MW} + DM_{\text{halo}} + \frac{DM_{\text{host}}}{1 + z} = 105$ pc cm$^{-3}$. For the characteristic value of $DM_{MW} \sim 45$ pc cm$^{-3}$, corresponding to the maximum of the lognormal distribution, we obtain that the total contribution of the matter of the host and the halo of our Galaxy to the dispersion measure is $DM_{\text{halo}} + \frac{DM_{\text{host}}}{1 + z} \sim 60$ pc cm$^{-3}$, which corresponds to the currently accepted value of $DM_{\text{halo}} \sim 30$ pc cm$^{-3}$ [13], provided that the contribu-

Fig. 15. Dynamic spectra and profiles of pulses.
tions of the matter of halo of our Galaxy and the matter of the host galaxy are equal.

It should be specially noted that a small number of scattering screens ≤ 3 along the path of propagation of FRB is independently indicated by the shape of the pulses observed at a frequency of 1.4 GHz, which is close to the decaying exponent for the overwhelming number of radio bursts. Specially conducted mathematical modeling clearly shows how the shape of the pulse changes when passing an increasing number of scattering screens. In full accordance with the central limit theorem, the shape of the pulse tends to the Gaussian with an increase in the number of screens, as shown in Fig. 9.

![Dynamic spectra and profiles of pulses.](image)
Analysis of logN – logS dependencies at two frequencies shows that, in general, these dependencies correspond to each other and none of them follows exactly the law $S^{-3/2}$. If we assume that the observed pulse samples are statistically equivalent, then we can deduce their average spectral index, which is equal to $\alpha = -0.63 \pm 0.20$. This value generally corresponds to the expected negative value, although a number of authors prefer to give steeper indices $\alpha = -1.8 + 1.5$.

**Fig. 17.** Dynamic spectra and profiles of pulses.
7. CONCLUSIONS

Attempts to detect radio bursts at low frequencies have been made repeatedly by many researchers abroad. These observations can be briefly described as unsuccessful, since no radio bursts were detected at frequencies below 300 MHz. This is an occasion for the authors [35] to comment on the results presented in [10, 11]. In this regard, it was necessary to conduct a special investigation and carefully analyze foreign observations dedicated to the search for FRBs in order to understand the reason for their non-detection.

Table 3 was compiled, which summarizes the observational parameters of the conducted surveys and special observations. It shows the observational...
frequency (MHz), the reception band (MHz), the sampling interval (s), the total duration of observations (h), the area in the sky (sq. deg) covered by the survey, and the threshold sensitivity (Jy). It immediately draws attention to the fact that the total duration of observations with the LPA is orders of magnitude higher than all previous observations (about $6 \times 10^5$ individual scans were analyzed). From this parameter and the total number of pulses detected with the LPA, it can be easily estimated that it takes about $10^3$ hours or $10^4$ scans on our antenna to detect
a single pulse. Another parameter that strongly distinguishes the LPA radio telescope from other instruments is the threshold sensitivity of the radio telescope (Jy). In many works, the limiting fluence (Jy ms) is given. It was converted into a threshold sensitivity based on the specified sampling time or pulse duration. The sensitivity of radio telescopes of foreign colleagues is orders of magnitude worse than the sensitivity of the LPA.

In addition, if it is not possible to detect pulses with well-tested methods, this means that non-standard methods are necessary, such as the correlation tech-

Fig. 20. Dynamic spectra and profiles of pulses.
Table 1. Dynamic spectra and profiles of pulses.

The main results of this work:

1. The shapes of the $DM$ distribution constructed for detected pulse signals at 111 MHz and FRBs at LPA level, then FRBs will be detected with these instruments as well.
1400 MHz coincide within the error and are described by the formula for the lognormal distribution with the parameters $\mu = 6.2$, $\sigma = 0.7$.

2. The dependence of the scattering $\tau_{sc}$ on the dispersion measure $DM$ for pulse signals recorded at a frequency of 111 MHz and FRB at 1400 MHz is constructed. The exponent $k = 0.49 \pm 0.18$ of the dependence $\tau_{sc} \sim DM^k$ within the error coincides with the exponent $k = 0.43 \pm 0.15$ of dependence $\tau_{sc}(DM)$ for pulses at 1.4 GHz.
3. The obtained power dependence is weaker in comparison with the dependence for pulsars and is explained by the fact that the matter of the intergalactic medium can be considered almost homogeneous compared to the matter of the interstellar medium. Thus, the intergalactic medium does not significantly contribute to the scattering of pulses. The main contribution to the scattering of pulses is made by the matter of the host galaxy and the galaxy in which the observer is located.

4. The scattering value at 111 and 1400 MHz is described by the law $\tau_{\text{sc}}(f) \sim f^{-1.9\pm0.7}$ and, thus, differs from the dependence $f^{-4}$ derived for pulsars.

Fig. 23. Dynamic spectra and profiles of pulses.
5. An estimate was made of the total component $DM_{\text{halo}} + \frac{DM_{\text{host}}}{1+z} \sim 60$ pc cm$^{-3}$, which is determined by the contribution of matter from the host galaxy and the halo of our Galaxy to the dispersion measure of radio bursts. This value depends on the model of the distribution of matter in the Galaxy and can be corrected in the future.

6. Based on the log$N$–log$S$ dependencies constructed for detected pulses at 111 MHz and FRB at 1400 MHz, the average spectral index $\alpha = -0.63 \pm 0.20$ is derived under the assumption of equality of the statistical properties of these samples.

7. Analysis of the form of log$N$–log$S$ dependencies at two frequencies shows that for $F_{111\,\text{MHz}} > 200$ Jy ms
and $F_{\nu,GHz} > 50$ Jy ms, both of them follow the law $S^{-3/2}$.

8. According to the totality of the detected observational signs: equality of $DM$ distributions, the exponent $k$ of the dependence $\tau_{\text{sec}} \sim DM^k$ coinciding within the error, and the following the law $S^{-3/2}$ of the log-$N$–log-$S$ curves at frequencies of 111 and 1400 MHz, we associate the detected pulse signals with FRBs. Thus, a frequency of 111 MHz is the lowest frequency at which radio bursts are detected.

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