PHYSICS OF OUR DAYS

Fast radio bursts

S B Popov, K A Postnov, M S Pshirkov

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Abstract. First discovered in 2007, fast radio bursts (FRBs) are highly luminous ($10^{-1} - 10^2$ Jy), millisecond-scale, highly dispersive single radio pulses whose record high brightness temperatures suggest a nonthermal emission mechanism. As of March 2018, a total of 32 FRBs have been recorded. There is also one repeating source, from which hundreds of bursts have already been detected. The rate of events is estimated to be several thousand per day per sky (disregarding bursts from the repeater), and their isotropic distribution in the sky suggests a likely cosmological origin. While numerous hypotheses have been proposed for FRBs since their discovery, the origin of these transients is not yet known. The most promising models either relate them to burst-type radiation from magnetars (neutron stars powered by the dissipation of their magnetic energy) or consider them analogous to giant pulses from some radio pulsars (strongly magnetized rotating neutron stars). The increasing statistics on the observed bursts and improvements in characterizing the FRB population will allow FRBs to become another tool for probing the intergalactic medium, estimating the cosmological parameters, and testing fundamental physical theories.

Keywords: fast radio bursts, neutron stars, radio astronomy, transient sources

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1. Introduction

Transient (i.e., rapidly emerging for a relatively short time) cosmic electromagnetic sources provide a wealth of information about astrophysical objects. Their observations in different electromagnetic bands constitute an important part of modern astrophysical research. The transients can be related to well-known objects (for example, flaring stars), can be repeating (for example, giant pulses of pulsars), or can be associated with unique events (for example, supernova explosions or binary neutron star coalescences). The detection efficiency of transient phenomena clearly depends on the sensitivity of a given detector, its field of view, and the duration of the transient, as well as on the background level and possible interferences.

In different electromagnetic bands, astronomical observations of transients have their own peculiarities. In the radio band, which is mainly discussed in this review, many different types of transients have been observed (see, e.g., review [1]). Some of them remain unidentified with other astronomical source, and their nature remains obscure. For example, the source GCRT J1745-3009 in the galactic center [2, 3] demonstrates outbursts typically lasting minutes with an observed flux of about 1 Jy. There are longer transients (for example, flares from active galactic nuclei), and there are much shorter ones.

Figure 1. Radio transients on the $L_\nu - \nu W$ plane. The straight lines correspond to constant brightness temperatures T_b. Shown are pulsars (PSRs), rotating radio transients (RRATs), millisecond pulsars (mPSRs), giant pulses from pulsars (GRPs), active galactic nuclei (AGNs), supernovae (SN), X-ray binaries, RS CVn and Algol stars (RSCVs, Algols), magnetic cataclysmic variables (magnetic CVs), normal (Main sequence) stars and brown dwarfs.

Here, we consider fast transient radio flares observed by modern radio telescopes at frequencies from hundreds of MHz to several GHz. Among the large variety of radio transients (see, e.g., [1]), the most interesting at present are the so-called 'fast radio bursts' (FRBs), discovered in archive data of the Parkes Radio Sky Survey in 2007 [4]. It is natural that their unusual properties, such as short durations $W \sim 1 - 10$ ms, high radiation intensities (the peak spectral flux density S_ν up to hundreds of Jy [1]), large dispersion measures [2] DM ~ 500 pc cm^{-3}, and a high sky event rate of the order of several thousand per day [5] arouse much interest.

1.1 Nonthermal emission from fast radio bursts

A distinctive feature of FRBs is their large dispersion measure, significantly exceeding that due to the galactic plasma in a given direction. This suggests large distances to these sources, indicating their extragalactic nature. This conclusion is also supported by the isotropic sky distribution of FRBs (as long as this can be inferred from the small source statistics and inhomogeneous sky coverage in different radio surveys). The high intensity and short duration of FRBs suggest a high brightness temperature of radio emission, pointing to a nonthermal (coherent) radiation mechanism. In the Rayleigh–Jeans limit ($h\nu \ll k_B T$), the brightness temperature T_b is determined by

$$k_B T_b = I_\nu \frac{c^2}{2\nu^2} \, , \qquad (1)$$

where I_ν [W m^{-2} Hz^{-1} sr^{-1}] is the radiation intensity, c is the speed of light, ν is the frequency, and k_B is the Boltzmann constant. Assuming the angular size of a source θ and casually

bounded burst duration, $W \sim l/c$, where $l = D\theta$ is the transverse size of the source at a distance D, we obtain the brightness temperature estimate

$$2\pi k_B T_b = \frac{S_\nu D^2}{(W\nu)^2} \, , \qquad (2)$$

or, with the characteristic values inserted,

$$T_b \approx 10^{35.8} \left(\frac{S_\nu}{1 \text{ Jy}} \right) \left(\frac{(D/1 \text{ Gpc})}{(\nu/1 \text{ GHz})(W/1 \text{ ms})} \right)^2 [\text{K}] \, . \qquad (3)$$

(Here, all quantities are given in the observer's rest frame). If the source is moving relativistically, this expression for the brightness temperature in the source's proper rest frame should be reduced by the Lorentz factor of the emitting region $\gamma \gg 1$.[3] These estimates show that even for FRBs at galactic distances (a few kiloparsecs), the brightness temperature is definitely higher than 10^{12} K.

Following [1, 7], it is convenient to present different populations of radio transients on the $L_\nu - \nu W$ plane, where ν is the pulse width and L_ν is the luminosity per unit frequency (see Fig. 1).

In radio astronomy, the 'pseudoluminosity' $L_{\text{psd},\nu} = S_\nu D^2$ obtained from the observed flux and the source distance estimate, which is commonly identified with the specific luminosity L_ν, is frequently used. We follow this tradition to display sources in Fig. 1.

At brightness temperatures above $\sim 10^{12}$ K, the radiation from cosmic sources should be nonthermal (coherent), because at higher temperatures thermal electrons would rapidly cool down due to Compton losses [8]. The radio

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[1] The Jansky (Jy) is the unit of spectral flux density used in radio astronomy, 1 Jy $= 10^{-26}$ W m^{-2} Hz^{-1}.

[2] The dispersion measure (DM) is the integral of the electron number density along the line of sight to the source, DM $= \int n_e \, dl$. DM is measured in units of [cm^{-3} pc], were the distance 1 parsec (pc) $\approx 206,265$ a.u. $\approx 3 \times 10^{16}$ m.

[3] From relativistic kinematics, in passing from the laboratory frame (K) to the rest frame (K′), we have $I_\nu = I'_{\nu'} \mathcal{D}^3$, $\nu = \nu' \mathcal{D}$, $\mathcal{D} = 1/[\gamma(1 - \beta\mu)]$ is the Doppler factor, $\gamma = 1/(1 - \beta^2)^{1/2}$ is the Lorentz factor, $\mu = \cos\theta$, θ is the cosine of the angle between the velocity vector and the direction to the observer in K. For $\gamma \gg 1$, we have $\mathcal{D} \approx \gamma$, and from (1) we then find $T_b \approx T'_b \gamma$. Another, more phenomenological, derivation of this result can be found in [6].

emission from pulsars, rotating radio transients (RRATs), and FRBs belongs to this class. The radio emission from some X-ray binaries, nova stars, flaring stars, and brown dwarfs, as well as from most supernovae, is thermal and noncoherent in most cases.

1.2 Energy release in fast radio bursts

The power of FRBs is one of their important characteristics. Estimating the specific radio luminosity of a source at a distance D from the observed spectral flux density S_v, assuming emission into a solid angle $\Delta\Omega$, $L_v = 4\pi D^2 S_v \Delta\Omega/(4\pi)$, and setting the energy released in the burst equal to $\Delta E = v L_v W$, we find

$$\Delta E \sim v S_v W 4\pi D^2 \left(\frac{\Delta\Omega}{4\pi}\right) = 10^{39} \, [\text{erg}] \left(\frac{v}{1 \, \text{GHz}}\right)$$
$$\times \left(\frac{S_v}{1 \, \text{Jy}}\right) \left(\frac{W}{1 \, \text{ms}}\right) \left(\frac{D}{1 \, \text{Gpc}}\right)^2 . \qquad (4)$$

The relativistic motion of the source decreases this value in the source rest frame K' by the factor $\mathcal{D}^3 \simeq \gamma^3$ (assuming isotropic emission in K', whence $\Delta\Omega'/(4\pi) = 1$).

For sources at cosmological distances, the energy release in a short coherent burst requires radiation mechanisms in relativistic plasma (see Section 4.2 below). For sources at galactic distances (10 kpc), the energy output of $\sim 10^{29}$ ergs is comparable to that characteristic of stellar flares, which was used as a starting point for a Galactic model of FRBs [9].

1.3 Features of detection of fast radio bursts

The propagation of a radio pulse in the ionized interstellar medium (ISM) or in the intergalactic medium leads to the broadening of the detected pulse (see [10] for more details). In the first place, the pulse widens due to the frequency dependence of the refractive index of the ionized medium (the dispersion measure effect). For a cold plasma, $n = [1 - (\omega_p/\omega)^2]^{1/2}$, where ω_p is the plasma frequency. The pulse time delay at different frequencies is determined by the dispersion measure DM:

$$t_{\text{DM}} \approx 4.2 \times 10^3 \, \text{DM} \left(\frac{v}{1 \, \text{GHz}}\right)^{-2} [\mu s] . \qquad (5)$$

For a noncoherent (channel-wise) dedispersion (removal of the pulse time delay at different frequencies due to the dispersion measure), the pulse width in the receiver band Δv at a frequency v is

$$\Delta t_{\text{DM}} \approx 8.3 \, \text{DM} \, \frac{(\Delta v/1 \, \text{MHz})}{(v/1 \, \text{GHz})^3} [\mu s] . \qquad (6)$$

For optimal registration, the signal is 'dedispersed'; therefore, the inevitable error in the dispersion measure, δDM, additionally increases the pulse width by about $\Delta_{\delta\text{DM}} = \Delta t_{\text{DM}}(\delta\text{DM}/\text{DM})$. Next, the pulse width increases because of a finite receiver bandwidth, $\Delta t_{\Delta v} \sim \Delta v^{-1}$. Finally, the pulse width increases by an amount τ_d due to the scattering on density fluctuations of the turbulent interstellar and intergalactic medium (the scintillation effect). To date, the last effect has been observed only in some FRBs; for other sources, only the upper bounds have been found. Like the dispersion measure time lag, the pulse width can increase along the entire path from the source to the observer. A significant enhancement of the FRB pulse broadening over galactic pulsars supports the extragalactic origin of FRBs. The existing data do not allow us to uniquely determine where the pulse widening occurs: either near the source in its host galaxy or somewhere between the source and the observer [11–13]. The measured pulse scattering width τ_d varies greatly from source to source and can amount to several msec at a frequency of 1 GHz. For several FRBs, the frequency dependence of this broadening was found, $\tau_d \sim v^\alpha$ with $\alpha \sim -4$. The fast growth in the pulse width caused by the scattering can also be a reason preventing FRB observations at low frequencies (see below).

The total pulse width increase is approximately

$$\Delta t = (\Delta t_{\text{DM}}^2 + \Delta t_{\delta\text{DM}}^2 + \Delta t_{\Delta v}^2 + \tau_d^2)^{1/2} . \qquad (7)$$

Unlike the scattering effects, the interstellar dispersion effects can be partially or fully removed by dedicated signal processing. As in searching for transients, the dispersion measure is not known in advance: it is chosen such that the signal dispersion after the dedispersion procedure is minimal, $\Delta t \to \Delta t_0 = (2\Delta t_{\text{DM,min}} + \tau_d^2)^{1/2}$.

After the dedispersion, pulses with an amplitude exceeding some threshold signal-to-noise ratio (S/N) are searched for in the records. Because the duration of the pulse W_i is unknown, its value is chosen to maximize S/N. For the root-mean-square (rms) noise amplitude σ_n and the pulse amplitude S_i (or its fluence $A_i \approx S_i W_i$), the optimal SNR is

$$\left(\frac{\text{S}}{\text{N}}\right)_i = \left(\frac{(A_i/W_i)}{\sigma_n}\right) \sqrt{\frac{W_i}{W_n}} , \qquad (8)$$

where W_n is the radiometer noise correlation time. As in radio dishes, $\sigma_n \simeq S_n/\sqrt{\Delta v W_n}$, where S_n is the antenna noise in Jy, the optimal signal-to-noise ratio does not depend on W_n, $(\text{S/N})_i \propto A_i/\sqrt{W_i}$, and the narrower the pulse is with a given fluence, the higher its detection signal-to-noise ratio. Of course, for a large fluence (strong signal), even wider pulses can be easily detected.

A radio pulse propagating in the ISM becomes wider, as discussed above, with its fluence being constant. If the pulse width due to the propagation and detection effects exceeds the intrinsic pulse width, $W_b > W_i$, the optimal S/N changes correspondingly as $(\text{S/N})_b = (\text{S/N})_i \sqrt{W_i/W_b}$. Clearly, the pulse widening due to propagation in the ISM significantly complicates the signal registration.

Here, we make one more physical note. For radio pulses with a high brightness temperature, the induced scattering effects in the surrounding medium (Compton scattering on electrons and Raman scattering on plasmons) can be significant. These effects were investigated in [14]. It was shown that during the propagation of a single pulse in a medium, the optical depth is mainly determined by the pulse width Δt, and the induced scattering is important only in plasma near the source (for example, in the pre-supernova stellar wind in the case of radio emission from gamma-ray bursts). The induced scattering effects inside the source itself can be ignored if the pulse is generated in a relativistically moving plasma. This made it possible to obtain a lower bound on the Lorentz factor of plasma inside the FRB, $\gamma > (3-4) \times 10^3$, which is relatively insensitive to the model parameters. We note that this condition is satisfied both for giant radio pulses generated in pulsar magnetospheres and for the magnetar model of FRBs discussed below in Section 4.2.2, and significantly restricts [15] (in addition to other arguments) the possibility of galactic generation of FRBs in stellar flares.

Despite the huge interest in the FRB phenomenon and the increasing number of papers devoted to the FRB problem, the nature of FRBs remains unknown. Frequently (and correctly) this situation is compared to the initial studies of cosmic gamma-ray bursts (GRBs) in the 1970s–mid-1990s, until the first optical identification of a GRB in a remote galaxy firmly established its extragalactic origin (see, e.g., review [16]). Therefore, until the distance to FRBs is measured from astronomical observations, a plethora of possible physical models remains possible.

Below, after a brief discussion of the history of FRB studies, we consider the main phenomenological properties of FRBs as a new astronomical phenomenon (Section 3), with a separate description of the presently unique repeating FRB 121102 (Section 3.2). Next, we discuss different scenarios proposed to explain FRBs in more detail, presenting the two most likely extragalactic FRB models: the FRB model as a noncoherent collection of nanosecond giant pulses from young pulsars (Section 4.2.1) and the model of synchrotron maser emission during giant bursts from magnetars (Section 4.2.2). In Section 4.3, we discuss extragalactic FRBs as possible intergalactic medium probes and their cosmological implications. In the Conclusion, the prospects for FRB studies are summarized.

2. History of FRB research

In this section, we present a brief review of the most important episodes in the short history of early FRB studies.

2.1 Early FRB studies

The discovery of Rotating Radio Transients (RRATs) [17] can be considered a precursor to the discovery of FRBs. These sources demonstrate separate repeating millisecond radio bursts. As described in [10], to identify single short radio flares, it was necessary to develop a complicated technique. In the case of RRATs, the analysis revealed a periodicity in records from a given source, which eventually allowed the identification of RRATs as a subgroup of radio pulsars — rotating neutron stars.

Presently, more than a hundred RRATs are known. The mechanism of generation of these short intense radio bursts remains unclear. However, studies of the activity of these sources suggested that they are radio pulsars with extreme nulling (i.e., a temporary absence of any radio emission), exceeding 95% of the pulsar spin period [18].

Importantly, RRATs were discovered using single-pulse searches, i.e., not due to searches for periodic radio emission, as in the case of radio pulsars. Therefore, in recent years, an effective method for robust identification of significantly dispersed single millisecond radio bursts from astronomical sources was developed. This paved the way for the discovery of an absolutely new phenomenon, the FRBs.

The first FRB discovery was announced in autumn 2007 [4]. The burst itself was observed in 2001, and was later named FRB 010724 (year–month–day). It was discovered by the 64-meter radio telescope in Parkes (Australia) during a radio pulsar survey at the frequency of 1.4 GHz. The observed flare position was three degrees off the Small Magellanic Cloud. The signal demonstrated a very large peak flux, exceeding 30 Jy, and a short duration < 5 ms. The key feature of this burst was its huge dispersion measure: $DM = 375$ pc cm^{-3}. This was significantly larger than the Milky Way contribution in this direction (see the standard

model of the galactic electron number density distribution in [19] and the new model in [20]). Follow-up observations lasted 90 hours, but no new flares were detected. Because the event was discovered during a survey, it was possible to estimate the rate of such events in the sky. Assuming that the dispersion measure was due to the contribution from the intergalactic medium, the authors obtained a rate estimate of 90 bursts per day in the fiducial volume of 1 Gpc^3. This roughly corresponds to thousands of bursts every day in the whole sky. It is interesting to note that after the discovery of more than thirty FRBs, this rough estimate is still valid up to a factor of the order of unity.

Soon after the first observational publication on FRBs [4], several theoretical papers appeared. In some of them, the ideas already proposed in the discovery paper were developed, while in others, new hypotheses were put forward. However, without new observational data, the topic was not actively studied.

The detection of the second burst, FRB 010621, was announced only in 2012 [21]. The burst was observed in one of the side lobes of the Parkes Telescope. The width of the pulse was 7.8 ms and no consequent flares were detected. Also, this burst was nearly two orders of magnitude weaker than the first one and was found close to the galactic plane. Therefore, the event looked much different from the first Lorimer burst. Taking the problems of perytons into account (see the next subsection), it was not obvious whether these two events represented a new class of astrophysical phenomenon. Archival searches of records from different radio telescopes (first and foremost those working at lower frequencies, several hundred MHz) gave null results.

The breakthrough happened thanks to paper [22] reporting the discovery of four new bright millisecond radio transients with large dispersion measures at high galactic latitudes. This publication can be considered the starting point of the modern history of FRBs.

2.2 Perytons

In the short history of FRBs, there is a notable episode related to the discovery of short radio bursts — so-called perytons. This type of short radio bursts was identified soon after the publication of the paper by Lorimer et al. [4]. As in the case of FRBs, the discovery of these events was due to the analysis of archive records of the Parkes Telescope [23].

In the first paper about the new type of radio transients [23] (in which the popular name of this phenomenon was proposed), the authors presented data on 16 events, each lasting for about ten milliseconds. In contrast to FRBs, perytons were recorded in all (or many) lobes of the Parkes dish. These events were nonuniformly distributed over the time of day or the season. Most of them occurred during working hours late in the morning. All perytons had similar spectral characteristics. Signals were delayed at lower frequencies, similarly to the dispersion effect in the interstellar (or intergalactic) medium. The frequency dependence of the time shift δt was very similar to the classical law $\delta t \sim v^{-2}$, but significant variations were observed for some events. Some bursts could come in series (for example, 11 flares were once detected in less than five minutes).

The authors of [23] immediately proposed that perytons could have a terrestrial, most likely technogenic origin. We note that at that time only one FRB (the Lorimer burst) was known. Formally, for many perytons, it was possible to

determine the dispersion measure. The obtained values were about $350-400$ pc cm^{-3} (see Fig. 9 in [24]), which is extremely close to the DM of the Lorimer burst, 375 pc cm^{-3}. Thus, the origin of the only known FRB could be questioned: was it an astrophysical phenomenon or did it have a terrestrial (even technogenic) origin, like perytons?

Perytons have been searched for using several radio telescopes (Arecibo, K Jansky VLA, and Allen Telescope Array), and new observations were made at Parkes (see a review and references in [24]). However, only at the Bleien observatory in Switzerland were similar signals detected [25].

The possible origin of perytons was analyzed in detail in several papers (see [24, 25] and the references therein). Many different hypotheses were put forward: atmospheric discharges, meteors, and various technogenic processes (e.g., a transit of an aeroplane in the field of view of a radio telescope). However, it was not possible to choose a model that was able to explain all observed features of perytons.

The solution came unexpectedly. In December 2014, new equipment for monitoring RFI (radio frequency interference) was installed at Parkes. Then, a very detailed study to uncover the origin of perytons was performed. This included new observations and data mining [27]. Simultaneously with Parkes, observations were performed with the Australia Telescope Compact Array (ATCA) and with the Giant Meterwave Radio Telescope (GMRT) in India. Only at Parkes were perytons detected, and it became clear that this was a local problem. Also, in addition to a signal at 1.4 GHz, the monitoring system detected emission at 2.3–2.5 GHz, apparently of a technogenic origin.

A careful analysis (and experiments!) indicate that perytons appeared from microwave ovens at the observatory! For a particular orientation of the telescope, when the door of an oven was opened while it was still working (recall how long you wait when heating up a cup of tea), a peryton was detected at a frequency of 1.4 GHz.

Additional studies revealed that FRBs, known at that time (including the Lorimer burst), do not have peculiarities typical of perytons. Thus, the astrophysical origin of FRBs seemed to be robust. However, the exact nature of these sources remained unknown.

3. Modern observations and phenomenology of fast radio bursts

Interest in FRB studies strongly increased after publication of paper [22] reporting four new events found in the archival Parkes records. Presently, more than 30 FRBs are known and one repeating source has been detected. The online catalogue of FRBs is available at http://frbcat.org [28]. Reviews dedicated to current FRB studies regularly appear (see [29, 30] and the references therein).

3.1 Single (nonrepeating) bursts
Presently, more than 30 single (nonrepeating) fast radio bursts are known. Most of them (25 events) were detected with the 64-meter telescope at Parkes. Five FRBs were detected by UTMOST (Australia). In addition, FRBs have been detected by ASKAP (Australia) [31] and the Green Bank Telescope (GBT) (USA). Five bursts were detected by the Australian facility UTMOST (Upgrade of The Molonglo Observatory Synthesis Telescope). The number of new sources is steadily increasing. The sky distribution of known sources is shown in Fig. 2.
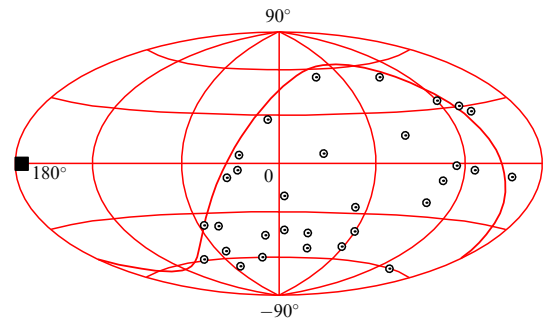
Figure 2. (Color online.) Sky distribution of known FRBs (circles) in galactic coordinates (latitude increases from right to left). The position of the only known repeating source FRB 121102 is marked with a solid square. The solid (red) line shows the celestial equator. Because most FRBs have been detected by Australian instruments, the north–south asymmetry is visible. (Data from the online catalogue frbcat.org.)

The typical peak flux of FRBs is ~ 1 Jy. However, for bright events (e.g., FRB 010724, and FRB 170827) it reaches tens of Jy, and for extreme cases, like FRB 150807, it exceeds 100 Jy!

The pulse width of detected events lies in the range from a fraction of a millisecond up to 30 ms. In some cases, there is a microstructure inside a narrow pulse. For example, the very bright event FRB 170827 recently detected by UTMOST almost in real time had a pulse width ~ 0.4 ms and demonstrated three subcomponents, the most narrow with a duration of only 30 μs [32]. Subpulses of a similar duration have also been observed in the repeating source FRB 121102 [33].

The sky distribution of known FRBs is significantly biased, because nearly all of them were detected by the Australian instruments (Parkes, UTMOST, and ASKAP). It is also important that many FRBs were discovered in archival pulsar survey data. Therefore, the sky coverage has not been uniform. However, a statistical analysis does not reject the hypothesis that the sky distribution of known FRBs is consistent with a uniform one.

Dispersion measures of FRBs span from ~ 170 to ~ 2600 cm^{-3} pc. The first dedicated search for events with a large DM of a few thousand cm^{-3} pc did not give any results [34]. However, several bursts with DM > 1500 cm^{-3} pc were discovered recently. The record belongs to FRB 160102 with DM $= 2600$ cm^{-3} pc [35].

FRBs have been mostly detected using archival data, which excludes effective searches for their counterparts at other wavelengths. The first burst discovered in real time was FRB 140514 [36]. This offered an opportunity to trigger urgent follow-up multiwavelength observations. No related transients were found. This made it possible to reject (at least for this particular source) all models related to supernova explosions, gamma-ray bursts, and some other bright transients that have been proposed as possible sources of FRBs.

In addition to FRB 140514, several other real-time detections have been made, including FRB 150215 [37], FRB 150418 [38], and FRB 150807 [39], as well as four events FRB 150610, FRB 151206, FRB 151230, and FRB 160102 reported in [35]. In all cases, there was no firm identification of any counterparts. This also allowed many models of FRBs to be ruled out.

FRB 150418 was proposed to be associated with a slow radio transient [38]. Based on this identification, a host galaxy of this FRB was identified. However, later on, it was demonstrated that these two radio sources are unrelated [40–42].

Moreover, the Fermi space observatory searched for gamma-ray FRB counterparts [43, 44] and associated GRBs [45]. No robust associations were found. In one case (FRB 131104), a gamma-ray burst with a duration of several hundred seconds was found [46]. However, this FRB–GRB association was later found to be unreliable [29].

Present-day observations of nonrepeating FRBs do not provide reliable information about the spectral properties of these events. The bursts have been detected in relatively narrow bands around the central frequency of either 1.4 GHz (Parkes, Arecibo) or ~ 840 MHz (UTMOST, GBT). Intensive searches at lower frequencies with various telescopes (including LOFAR, LOw Frequency ARray) gave null results [47–50]. In particular, the authors of [50], based on nondetection of FRBs at low frequencies and assuming a power-law spectrum in a wide spectral range (from a few centimeters to ~ 1 m), infer limits on the spectral index ($F \sim \nu^{\alpha}$, where F is the burst fluence): $-7.6 < \alpha < 5.8$. Nevertheless, considering the existing uncertainties, this result is not very constraining for FRB models.

Why FRBs have not been detected at frequencies below 800 MHz remains unclear. This can be an intrinsic property of the emission mechanism, but is more likely to be due to absorption at low radio frequencies. First, a major role can be played by the medium in the immediate surroundings of a source (see, e.g., [51]). An analysis of different possibilities and predictions for future low-frequency observations [for example, CHIME (Canadian Hydrogen Intensity Mapping Experiment) and HIRAX (Hydrogen Intensity and Real-time Experiment), which will operate at frequencies of ~ 600 MHz] can be found in [52].

Recently, FRBs have been searched for at frequencies of 300–400 MHz during the Green Bank Northern Celestial Cap (GBNCC) pulsar survey [53]. No FRBs have been found. The authors of [53] put constraints on the spectral index under different assumptions about source properties and parameters of the medium along the line of sight.

No new events have been found in a two-year search (518 hours of observations in the period from July 2015 to August 2017) in the project ALFABURST (a real-time fast radio burst) on the 305 m Arecibo radio telescope [54]. However, this is not unexpected, taking the small field of view of the telescope into account. The whole survey time is equivalent to the observation of a 10-square-degree field for one hour. The expected event rate of bright bursts in such a field is one per day. It was hoped that the higher sensitivity of the Arecibo Telescope could enable the detection of weaker bursts with a presumably much higher event rate. This null result corresponds to expectations and does not put significant constraints on the FRB spectra, the spatial distribution of bursts, or their luminosity function.

For several sources, the radio emission polarization was measured. The first case was FRB 110523 [55]. The signal was linearly polarized at the 44% level. The detection of a rotation measure RM $= -186.1 \pm 1.4$ rad m^{-2} allowed estimating the average magnetic field (weighted with the electron number density) along the line of sight: 0.38 μG. The analysis suggested that the local medium near the source most likely contributes to the rotation measure (contributions due to the

intergalactic medium and the interstellar medium in the Milky Way are relatively small).

By contrast, FRB 140514 demonstrated only circular polarization at the 20% level [36]. Later, three other linearly polarized sources were detected. In the case of FRB 150418, the polarization degree was 8.5% [38]. Such a low value did not enable any solid estimates of the magnetic field along the line of sight to be made. For FRB 150215, a 40% linear polarization was measured, but the RM was found to be compatible with zero (within the uncertainty range) [37]. By contrast, a very high polarization degree of 80% was reported for FRB 150807 [39]. The relatively small measured value of the rotation measure, RM ≈ 12 rad m^{-2}, suggests that the medium around the source is not strongly magnetized. This allowed the authors to put constraints on parameters of the intergalactic magnetic field and turbulence. The repeating source FRB 121102 is an outlier in this respect as well. It shows a nearly 100% linear polarization and a very large variable rotation measure: RM $\sim 10^5$ rad m^{-2} [33]. More details on this source are given in Section 3.2 below.

Statistical properties of FRBs have been examined in many papers (see, e.g., [56–59] and the references therein). Not surprisingly, up to now, the conclusions are highly uncertain due to the small number of known events.

Estimates of the FRB rate in the sky are being continuously updated. They fall within the range from a few thousand to a few dozen thousand events across the sky per day for fluences above a few dozen Jy ms. The weakest sources detected at Parkes have a fluence of 0.55 Jy ms. The data are considered to be sufficiently complete only for fluences $F > 2$ Jy ms.

The authors of [56] give the following estimate of the FRB sky rate:

$$\frac{\mathrm{d}N}{\mathrm{d}F} = (4.14 \pm 1.3) \times 10^3 \, F^{-1.14 \pm 0.2} \, \mathrm{d}^{-1} \,, \qquad (9)$$

(here, the fluence F is expressed in units Jy ms).

An estimate of 587 events per day for fluxes above 1 Jy is given in [60]. A more detailed estimate (for high and low galactic latitudes) is provided by the same authors in [61]. In [35], an FRB sky rate of 1.7×10^3 bursts per day was obtained based on a sample of FRBs detected at Parkes with fluences above 2 Jy ms.

In the zeroth approximation, we could assume that the peak flux distribution of FRBs ($\log N - \log S$) follows the law for a flat space, $N(>S) \sim S^{-3/2}$ (Fig. 3). The existing data demonstrate that this is not the case. However, this is not in contradiction to cosmological models of FRBs. In [57], the authors used statistical tests to show that the flux distribution of FRBs could be compatible with a uniform distribution in Euclidean space. The analysis presented in [59] suggests that the real flux distribution of FRBs is not significantly flatter than $S^{-3/2}$ (and can be even steeper).

The FRB fluence distribution is presented in Fig. 4. Here, the fluence [erg cm^{-2}] was determined as the product of the peak flux by the pulse width given in the catalogue. This distribution has a nontrivial shape. Two populations of sources can be distinguished, corresponding to the fluence ranges $0.5 < F < 3$ Jy ms and $3 < F < 100$ Jy ms. Interestingly, in each interval, the distribution can be fitted by a linear function $N = a - b \times F$, where a and b are positive coefficients that are different for two fluence ranges (see also [51], where such a property was noticed for the first time, as far as we know). This bimodality in fluences, as well as the linear
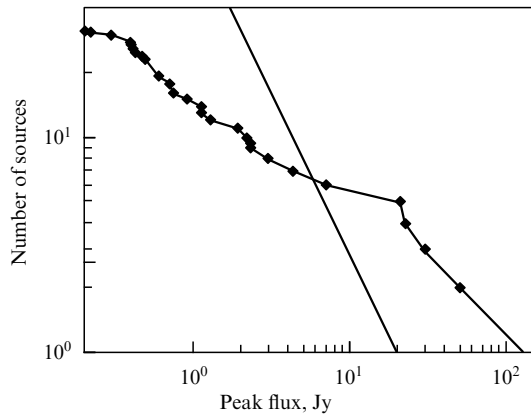
Figure 3. Integral peak flux distribution of fast radio bursts: $\log N(> S) - \log S_{\text{peak}}$. The solid line corresponds to the law $N(> S) \sim S^{-3/2}$. (Data from the online catalogue frbcat.org.)
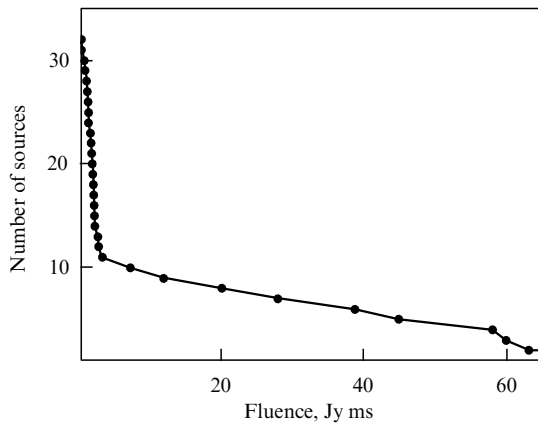
Figure 4. Integral fluence distribution of FRBs: $N(> F) - F$ (in a linear scale on both axes). (Data from the online catalogue frbcat.org.)

dependences in each fluence interval cannot be easily interpreted. Perhaps, this is due to observational selection effects or low statistics. In addition, of the 10–12 sources with the highest fluences, only about one half were discovered at Parkes. On the other hand, among the rest of known FRBs (which correspond to the second population with weaker fluences in the plot $N(> F) - F$), the Parkes events dominate.

3.2 Source of repeating bursts
FRB 121102 is unique among FRBs for several reasons. First, it was the first FRB source not detected at Parkes [62]. Observations of the source by the Arecibo 305 m telescope (Puerto Rico) firmly refuted FRBs as local Parkes artefacts. Second, it remains the only known source of repeating FRBs. Last, sufficiently frequent repeating bursts enabled determining the precise source coordinates and opened the possibility of simultaneous multi-wavelength observations.

The source was discovered in the archival data of the large pulsar survey in the galactic anticenter region (PALFA, 1.4 GHz Pulsar Arecibo L-Alpha Survey) aimed at detecting pulsars and related phenomena, e.g, RRATs, in the galactic plane ($|b| < 5°$). The observations were performed with a multi-beam receiver operating in the 322 MHz bandwidth centered at 1375 MHz with a high temporal resolution of

65.5 µs. (Seven beams with an FWHM of 3.5 arcmins were used.) Searches for single bursts were made using data dedispersion in a wide range of DM from 0 to 2038 pc cm^{-3}.

A single strong burst with S/N = 14 was found in the archival record of 2 November 2012. The burst swept through the frequency band of the detector at a rate corresponding to DM = 557.4± 2.0 pc cm^{-3}. It was observed in the fourth beam with the galactic coordinates of the beam center $b = -0.223°$, $l = 174.95°$ at the moment of observation, which were assigned to the burst. The burst localization was complicated by its detection in the sidelobe of the beam, and its location error exceeded 5 arcmins. One could expect a rather high dispersion measure at this low galactic latitude; however, the observed DM was almost a factor of three higher than the estimated galactic contribution in this direction DM$_{\text{NE2001}} = 188$ pc cm^{-3} (the index NE2001 refers to the model in [19] used for the dispersion measure calculation). In the absence of compact dense galactic structures that could significantly affect the observed DM, this clearly suggested an extragalactic origin of FRB 121102. The amount of 'excess DM' due to the extragalactic contribution allowed a rough estimate of the distance to the burst, $D \sim 1$ Gpc, which eventually almost coincided with the measured distance to the host galaxy (see below). The observations provided only upper bounds on the pulse dispersion widening, 3 ± 0.5 ms, also suggesting an extragalactic origin of the source.

There were no new bursts detected during the subsequent observations of this region in 2012–2013 with a total duration of several ks. Nevertheless, searches for repeating bursts were not terminated, and 10 additional bursts with the same DM were finally detected in this direction in May–June 2015. Thus, a novel phenomenon, a repeating FRB, was discovered [63].

The duration of repeating bursts from the source fell within the 2.8–8.7 ms range, typical for durations of known FRBs. However, fluxes of (0.02–0.3) Jy were on average an order of magnitude lower than those of the 'typical' FRB. The spectral index α in the power-law approximation $S(\nu) \propto \nu^{\alpha}$ varied from -10 to 14 for different bursts. No periodicity in the times of arrival of the bursts were found, and the situation has not changed since then, despite a large increase in the number of detected bursts.

Repeating bursts from this FRB raised enormous interest. Many instruments, primarily those operating at radio frequencies, commenced large observational programs aimed at observing FRB 121102. Almost immediately, this resulted in big success. The angular resolution of even the largest single-dish radio telescope is rather mediocre, and this considerably hampers the accurate identification of sources and their observations in other energy ranges. Interferometric observations at the VLA (Karl G Jansky Very Large Array) with its superior resolution allowed an improvement in the determination of the source position to 0.1 arcsec [64]. Nine bursts were detected in the 2.5–3.5 GHz band during the 83 hours of VLA observations, three of them with simultaneous observational coverage at Arecibo, which managed to detect only one of them. This shows that the bursts have a nontrivial spectral shape, which, according to the present data, is better described by a Gaussian curve with a width of 500 MHz. The high variability and the complex spectral structure of the bursts have been recently confirmed by observations with the Green Bank radio telescope (GBT) in the 4–8 GHz band: all 15 detected bursts showed a nontrivial

structure in the 0.1–1 GHz range, and the spectrum of some of them peaked at frequencies above 6 GHz [65].

In addition, a weak persistent source with the flux density $S_{3\,\mathrm{GHz}} = 180\ \mu\mathrm{Jy}$ at 3 GHz was detected inside the VLA error box. The large optical Gemini and Keck telescopes discovered a dim object whose position coincided with that of a persistent radio source. The detection of prominent Balmer and [O III] emission lines allowed the estimation of the source redshift $z = 0.193$ corresponding to the photometric distance $D = 972$ Mpc [66]. The object was identified as a dwarf galaxy with a diameter of 4 kpc and a stellar mass $M_* = (4-7) \times 10^7\ M_\odot$. The probability of the chance positional coincidence of the dwarf and the persistent source was estimated to be lower than 3×10^{-4}. The properties of the galaxy and the localization of the source inside it were refined after deep observations with the Hubble and Spitzer space telescopes: the source was associated with a compact star-forming region 0.7 kpc in diameter, located in the outskirts of a galaxy at a distance of 2 kpc from the nominal centroid of the diffuse emission [67]. The improved estimate of the galaxy stellar mass was revised upwards to $M_* = 10^8 M_\odot$. The metallicity of the host galaxy is low, $\log_{10}[\mathrm{O/H}] = -4.0 \pm 0.1$. Peculiar hydrogen-poor superluminous supernovae (SLSN-I) are known to preferably occur in such galaxies, and this may signal their relation to FRB 121102.

Further observations at the EVN (European VLBI Network) and VLBA (Very Long Baseline Array) radio telescopes revealed that the size of the persistent source was smaller than 0.2 mas (corresponding to a linear size of 0.7 pc at the 1 Gpc distance), its emission in the 1–20 GHz range was nonthermal, and the source diurnal variability was at the $\sim 10\%$ level. Its distance between the burst and persistent source is smaller than 12 mas (40 pc at the 1 Gpc distance), very likely suggesting their common origin [64, 68]. The observed flux of the persistent source at the 1 Gpc distance corresponds to the radio luminosity $L_\mathrm{R} \sim 10^{39}$ erg s^{-1}, and the luminosity of individual bursts can reach 5×10^{42} erg s^{-1}. The total energy of individual bursts from the source can be as large as $\mathcal{O}(10^{40})$ erg.

Deep observations with the Chandra and XMM-Newton (X-ray Multi-Mirror Mission) X-ray telescopes put only upper bounds on the X-ray luminosity of the persistent source in the 0.2–6 keV energy range: $L_\mathrm{X} < 3 \times 10^{41}$ erg s^{-1} [69]. Many models (for example, FRBs from magnetars) predict that powerful bursts with a much higher luminosity temporally coincident with a radio burst can emerge at other frequencies. The lack of detection of X-ray photons and gamma rays by Chandra and Fermi LATR (Large Area Telescope) coinciding with FRBs constrains the total energy of the associated flares: 4×10^{45} erg and 5×10^{47} erg, respectively [69]. Only upper bounds have been obtained for the possible optical counterparts [70]. Results of joint observations by the Arecibo radio telescope and VERITAS (Very Energetic Radiation Imaging Telescope Array System) Cherenkov telescope at very high energies above 100 GeV have not yet been reported [71].

The analysis of another 16 bursts discovered at Arecibo in the course of regular observations in the 4.1–4.9 GHz band [33] revealed a linear polarization degree close to 100% after correction for Faraday rotation. The measured rotation measure exceeded 10^5 rad m^{-2}. Moreover, the RM was highly variable: in GBT observations, the RM values decreased by 10%. This high rotation measure and its

variability could be due to the source being located in an accretion flow close to a supermassive black hole. The black hole, in turn, may be the persistent source detected near this FRB. The source is more likely surrounded by a young pulsar nebula, and the observed pulse properties can be explained by the propagation of the signal through its filamentary structure.

It is not surprising that the discovery of the repeating FRB and its host galaxy localization gave rise to many papers trying to explain all observed properties and to construct a model of FRB 121102. The recurring bursting activity observed over several years almost definitely excludes all catastrophic scenarios, e.g., an FRB from binary neutron star coalescences. In addition, the recurrence of radio bursts excludes a large number of 'nonconventional' models, such as collisions with asteroids and interaction with axion miniclusters. The source location in the outskirts of the host galaxy argues against models linking the generation of bursts to galactic nucleus activity. Successful models should also simultaneously explain the observed properties of the persistent source, the lack of the dispersion measure evolution, and statistical distributions of burst properties.

The most promising models (as in the case of nonrepeating FRBs) involve supergiant pulses of radio pulsars and strong flares of magnetars, because they provide a qualitative explanation of all observational data. As in the models of single flares, the repeating bursts are powered by the rotation energy or by the magnetic field energy (i.e., energy of the electric currents inside the neutron star).

We note that the magnetar model [72, 73] is slightly preferable from the standpoint of the burst power. The giant pulse model requires a very high conversion efficiency of the rotation energy into radio emission, exceeding that in the Crab pulsar by several orders of magnitude [74]. Both models involve young neutron stars with an age below 100 years, and the persistent source in both cases could be a pulsar (magnetar) wind nebula and/or a young supernova remnant.

The analysis of times of arrival of the bursts can also give valuable insights. The time distribution shows a strong clustering of bursts considerably deviating from a stationary Poissonian process but appears to be quite close to the similar distribution of flares produced by soft gamma-ray repeaters (SGRs) [75]. Despite the detection of more than 200 bursts, no periodicity was found. A strong indirect indication of periodicity is suggested by the observation of two pairs of bursts with a very small time separation (34 and 37 ms), which could be a consequence of a fast rotation of the neutron star with a period of 3 ms [76].

It is still possible that the rich phenomenology of repeating bursts is produced in the interstellar medium of the host galaxy rather than in the source itself. Strong nonhomogeneities of the electron density in the host galaxy could play the role of plasma lenses, considerably amplifying the signal and producing its spectral modulation [77].

Whether FRB 121102 is unique or belongs to a large class of sources is another very important question. A simple assumption of a uniform population, i.e., that all FRBs are repeating ones, is frequently used. However, this assumption is most likely invalid; otherwise, several repeating bursts should already have been detected in the Parkes data [78]. Given that the Parkes telescope has observed a large portion of the celestial sphere, this suggests that the repeating bursts are quite a rare (or short-lived) phenomenon.

4. Hypotheses on the nature of fast radio bursts

The problem of explaining the FRB phenomenon can be divided into two parts: the physical one, related to the emission mechanism enabling a very high brightness temperature and explaining other FRB spectral and timing properties, and the astrophysical one, considering specific astronomical objects or phenomena with the required FRB features (spatial distribution, event rate, energy release, transparency of the medium to radio emission with a high brightness temperature, etc.). Clearly, any realistic model should take both aspects into account, and this appears to be highly nontrivial.

More than two dozen hypotheses have been proposed to explain the FRB phenomenon. Several of these ideas are mentioned in brief review [79]. Some of the proposed models are based on exotic physics (cosmic strings, white holes, charged black holes, etc.), and some on more conventional scenarios.

We start with a list of models that are presently not considered viable explanations of the whole class of FRBs. Separately, we discuss coalescing neutron stars, because several years ago this scenario was considered to be one of the most preferable FRB mechanisms. We then focus on two models (magnetar flares and supergiant pulses of radio pulsars) that are now thought to be the most promising ones. We note that the FRB population can be nonuniform, i.e., not necessarily all sources should be described by a single model. In this respect, the only known repeating source is presently of special interest (see Section 3.2). After discussing different theoretical models, we consider FRBs as probes in cosmology, extragalactic astronomy, and fundamental physical theories.

4.1 Less probable hypotheses

Hypotheses about the nature of FRBs can be divided into two broad categories: those related to neutron stars and to exotic scenarios. On the one hand, neutron stars are well-studied sources of strong radio emission, including short bursts; on the other hand, neutron stars can easily both provide the necessary energy release and explain the short duration of radio flares. The latter is because the characteristic timescales — dynamical (close to the surface) and Alfvénic (in the inner magnetosphere) — are of the order of a few milliseconds. The appearance of various exotic models can be explained by the possibility of applying interesting nonstandard theoretical ideas to real observations.

Very soon after the announcement of the first FRB, a model of the generation of FRBs by cosmic strings was proposed [21]. In this model, a cusp (a peculiar point related to a kink) of a cosmic string is the source of electromagnetic emission. Later on, this approach was further developed in several other studies by different authors.

Another exotic scenario based on evaporation of a primordial black hole was mentioned in paper [21] reporting the discovery of the second FRB. Bursts of electromagnetic emission at different wavelengths emerging during this process were predicted already 40 years ago [81]. However, to explain observed FRB fluxes, it is necessary to place the sources at distances less than 300 pc.

An interesting modification of the evaporating black hole scenario was studied in [82] considering the appearance of a white hole at the late stages of black hole evaporation, which is possible in the loop quantum gravity theory. In this case,

the remaining mass of the object can be higher, enabling a more powerful signal that can be seen from larger distances than in the standard Hawking process.

Closing the list of exotic scenarios with single black holes, we mention paper [83], in which the authors considered the collapse of the magnetosphere of a rotating charged (Kerr–Newman) black hole. We stress that in the framework of this scenario, as well as in most of the other exotic schemes, it is difficult to explain all the observed characteristics of FRBs under realistic conditions.

At the other end (with respect to scenarios, including exotic physics) is the model of short radio flares from normal stars in our Galaxy [9]. This is an interesting example of the FRB model that was quickly criticized from different standpoints and rejected on various grounds (see [15, 84] and the references therein). We also mention that most of the current FRB models are based on the extragalactic nature of the sources.

Magneto-hydrodynamical mechanisms of FRBs were proposed in several studies. In one of them, the authors considered the bremsstrahlung radiation of a collisionless plasma with strong turbulence [85]. According to this model, an FRB can be a feature of a relativistic jet, in which a beam of relativistic electrons produces coherent radio emission due to interaction with plasma turbulence.

In [86], a binary system with a radio pulsar was analyzed. If an object (a planet, an asteroid, or a white dwarf) is embedded in a magnetized pulsar wind, two stationary Alfvén waves ("Alfvén wings") might appear. Due to instabilities, these stationary waves can generate radio emission. Because of relativistic beaming, a strong peak of the emission can be observed only if the observer is located exactly on the pulsar–object line. It is very difficult to explain some properties of FRBs with this model, especially the absence of periodicity related to the orbital motion of a body around a neutron star.

We continue with nonstandard scenarios involving neutron stars. In these models, a neutron star can be single or enter a binary system. For example, in the model proposed in [87], an FRB appears after a supernova explosion in a binary system where the second companion is a neutron star with a large magnetosphere. The supernova shock wave interacts with the magnetosphere, forming a magneto-tail. Plasma instabilities in the tail can result in coherent radio emission. A similar model, called the 'cosmic comb', was later developed in [88]. A problem with this model (as well as many others) is related to the impossibility of explaining the high event rate (in particular, because a specific orientation of the binary relative to the observer is required), and, of course, it is impossible to explain the repeating source.

As mentioned above, neutron stars are attractive for FRB models because of their strong magnetic fields enabling short radio pulse generation. This feature is employed in two models related to isolated neutron stars. In the first one [89], an asteroid falls onto a neutron star. As a result, a cloud of ionized matter is formed and expands predominantly along the magnetic field lines. The authors suggest that the coherent emission from a narrow layer on the surface of this fireball can be responsible for the FRB phenomenon.

According to the second model, elaborated in [90, 91], the crucial ingredient is the Primakoff process of conversion of axions into photons (or vice versa) in a magnetic field. Axions are popular particle candidates to explain dark matter. If they

are sufficiently abundant in the Universe, they can form clouds with masses of $10^{-12} - 10^{-11} M_\odot$ which can eventually fly through the magnetospheres of neutron stars. However, it was demonstrated in [92] that such an axion cluster would be destroyed by tidal forces before the collision, which extends the burst duration to a few seconds.

The deconfinement of the neutron star matter results in dramatic changes in neutron star interiors [93]. In a very short time (of the order of a millisecond), the radius and gravitational mass of the object change. This is accompanied by a huge energy release (mainly in the form of neutrinos). However, an electromagnetic burst can and should appear as well. Taking into account that the magnetic field of the object can also be significantly modified, a short radio flare can be generated. Two scenarios in which the deconfinement of a neutron star is accompanied by an FRB have been proposed [94, 95].

Finally, it is necessary to mention the FRB scenario with a supramassive neutron star [96]. A supramassive neutron star is a compact object that avoids gravitational collapse thanks to its rapid rotation. As the star spins down, the central density increases, ultimately resulting in a collapse into a black hole. At this moment, a short radio burst can be generated. This model allows a large time interval between the neutron star birth and the FRB emission. This is important because no FRBs discovered in real time have been accompanied by bright counterparts, like a supernova or GRBs. The authors of [96] assumed that the collapse can occur hundreds or even thousands of years after the neutron star formation. However, the analysis in [97] demonstrated that if a neutron star is formed during a binary system coalescence, the collapse most likely occurs within a few hours. The reason for such a rapid collapse is related to a very effective spin-down due to the strong magnetic field, which inevitably must be formed in this situation [97]. An FRB model from the collapse of a supramassive neutron star shortly after the coalescence of a close binary neutron star system was also considered in [98].

Coalescence of magnetized compact stars. In the foregoing, we already mentioned models related to binary neutron star coalescences. While such models are possible, it is clear that they cannot explain the whole population of FRBs and definitely not the repeating source FRB 121102. In the past, the binary coalescence model was quite popular because of the proposed identification of a long radio transient in the FRB 150418 error box [38]. However, further studies [41, 42] revealed that this transient is due to the activity of the galactic nuclei and is unrelated to the FRB. Thus, the association of FRB 150418 with an elliptical galaxy was found to be erroneous.

Initially, the coalescence of two magnetized compact stars producing an FRB was mentioned in [99, 100]. Then it was discussed in more detail in [101]. Of course, in the early studies (see, e.g., [99] and the references in [101]), the generation of radio emission accompanying the neutron stars' coalescence was considered; however, strong millisecond radio bursts were not discussed.

The binary neutron star coalescence is assumed to give rise to a massive rapidly rotating magnetized object, collapsing into a black hole. This allows the high luminosity and short duration of the burst to be explained simultaneously. A maximum energy release can be estimated using the standard equation for electromagnetic losses from a rotating magnetized body:

$$\dot{E} \approx 4 \times 10^{45} \left(\frac{B}{10^{13}\,\text{G}} \right)^2 \left(\frac{R}{10^6\,\text{cm}} \right)^6 \left(\frac{P}{1\,\text{ms}} \right)^{-4} \ [\text{erg s}^{-1}].$$

(10)

Here, B is the surface magnetic field, R is the body radius, and P is its spin period. As in the case of radio pulsars, only a tiny fraction of the total energy losses is emitted in radio waves. However, the observed FRB fluxes of $\sim 10^{-13}$ erg cm^{-2} s^{-1}, corresponding to a luminosity of the order of 10^{40} erg s^{-1} for distances of about several hundred Mpc, can be easily explained even for low conversion coefficients.

In [101], the radio emission mechanism was not specified. The authors of [102] analyzed in detail the unipolar inductor model as applied to FRBs during a binary neutron star coalescence (previously, this mechanism was discussed in [103], where the radio luminosity was shown to exhibit a power-law growth for different radio emission generation mechanisms with the typical timescale of the main burst of about a fraction of a second).

We note that the estimated FRB rate (about 100 events per day from a ~ 1 Gpc^3 volume) is too large to be explained by neutron star coalescences. The conservative estimate of binary neutron star coalescences of about once in 10^5 years in a Milky Way-like galaxy [104] can be recalculated to yield about 100 coalescences per year in a 1 Gpc^3 volume, which is much smaller than the FRB rate ($\sim 2-3 \times 10^3$ per day). Modern estimates of the binary neutron star coalescence rate, improved after the first detection of the gravitational wave signal from the binary neutron star merger event GW 170817 [105], is an order of magnitude higher, ~ 1540 per year in a 1 Gpc^3 volume, but this does not help much. No short radio transients have been detected from GW 170817 [106]; however, we note that the first radio observations started a few hours after the registration of the gravitational wave signal [107]. Nor can it be ruled out that the nonthermal radio emission after the neutron star coalescence in GW 170817 was strongly beamed.

Another variant of the FRB model based on the coalescence of magnetized compact stars was proposed in [108], where the coalescence of a neutron star with a black hole was considered. Here, it is assumed that the neutron star is not tidally disrupted until the latest stages of the coalescence. Thus, a black hole can enter into the neutron star magnetosphere (i.e., inside the light cylinder $R_l = c/\omega$). In the case of a nonrotating black hole, the radio luminosity can be calculated as [108]

$$L = 1.3 \times 10^{40} \ [\text{erg s}^{-1}] \left(1 - \frac{2M_{\text{BH}}}{r} \right) \left(\frac{v}{c} \right)^2 \left(\frac{B}{10^{12}\,\text{G}} \right)^2$$

$$\times \frac{\eta}{10^{-2}} \left(\frac{M_{\text{BH}}}{10\,M_\odot} \right)^2 \left(\frac{r_{\text{NS}}}{10^6\,\text{cm}} \right)^6 \left(\frac{r}{30\,M_\odot} \right)^{-6}. \quad (11)$$

Here, M_{BH} is the black hole mass, B is the neutron star surface magnetic field, r_{NS} is its radius, and r is the distance from the black hole to the neutron star surface. The efficiency of the radio emission η is normalized to 0.01, but can be higher for rotating black holes.

Presently, it is accepted that the rate of neutron-star–black-hole coalescence is smaller than that of double neutron stars [104]. Therefore, the authors of [108] suggested that only a small subpopulation of FRBs can be described by this

model. The authors also note that bimodal bursts, like FRB 121002 [5], can appear in this scenario.

Finally, coalescences of magnetized white dwarfs were also considered in [109]. In this case, the rotation energy losses are too low to power FRBs, and the authors of [109] additionally considered the energy release due to the reconnection of magnetic field lines. In this model, the coherent radio emission originates in the polar region of a rapidly rotating (spin period of the order of one second) white dwarf with a very high magnetic field exceeding 10^9 G. To provide the necessary burst power, about 1% of the magnetic field energy must be converted into radio emission. In this scenario, some FRBs can be accompanied by a type-Ia supernova if the total mass of the coalescing double white dwarfs exceeds the critical value (close to the Chandrasekhar limit $\simeq 1.4 M_\odot$). Up to now, no such FRB counterparts have been observed.

Many of the models considered not to be very realistic are related in some way to more plausible scenarios. More realistic models and their modifications are discussed in Section 4.2.

4.2 Most probable hypotheses

As mentioned in the Introduction, any realistic FRB model must simultaneously explain the high brightness temperature of radio emission, the short burst duration and its energy, and provide the required occurrence rate, the spatial distribution, and other observed properties (see Section 3 for more details).

4.2.1 Giant pulses of radio pulsars. Several radio pulsars are known to occasionally emit giant pulses (GPs). The best-studied example is the young pulsar in the Crab nebula. The giant pulses are short (up to several microseconds) radio bursts with the peak flux exceeding that of the mean pulse by several orders of magnitude. Dedicated observations have revealed a complex nanostructure of Crab GPs: a giant pulse is resolved into a sequence of much shorter nanoshots, which collectively form the giant pulse shape.

Record high-intensity nanoshots were observed at 9 GHz in a 2 GHz bandwidth. Nanoshots remained unresolved, despite the large bandwidth and the correspondingly high temporal resolution, implying that their duration W was less than 0.4 ns; the highest observed peak flux density exceeded 2 MJy [110]. In the nonrelativistic case, this would imply emission from a region less than $cW \sim 10$ cm in size and the corresponding brightness temperature higher than 2×10^{41} K. Relativistic corrections due to velocities with a bulk Lorentz factor $\gamma \sim 10^2 - 10^3$ increase the size to $10^3 - 10^5$ cm and decrease the brightness temperature to still huge values: $10^{35} - 10^{37}$ K. Undoubtedly, nanoshots are generated coherently in rather compact regions.

The origin of GPs, as well as the nature of pulsar radio emission in general, remains unclear as yet. GP properties were used as starting points for FRB models for both FRB and GP models from neutron stars observed from large distances [111–113].[4] In this model, an FRB is a collection of a very large number ($N_i \sim 10^{12} d_{Gpc}^2$, where d_{Gpc} is the FRB distance in Gpc) of nanoshots, which are similar to the 'record' GP observed from the Crab pulsar (see above).

FRBs can be produced in this model only if the relativistic plasma inside the pulsar magnetosphere is endowed with fairly extreme properties, which, nevertheless, can be realized in nature. Energy estimates suggest that the most natural candidates could be neutron stars with ages smaller than 100 years and spin periods shorter than 20 ms, giving the model its name, the 'young neutron star model'. In it, the bursts occur at modest cosmological distances. In order to reproduce the observed FRB rate, each individual source must produce $10^4 - 10^5$ bursts during its active phase. This number is small enough to be consistent with the fact that there is only one repeating FRB known (FRB 121102), which, however, might belong to another class of sources (see Section 3.2). A search for a nanostructure in the bursts could serve as a direct observational test of the model; however, such searches can be severely hindered by the effects of propagation of short radio pulses in the interstellar and intergalactic medium.

The model was further developed in [51]. By assuming the FRB formation from rapidly rotating (millisecond) very young pulsars, the authors considered the dispersion measure change in a young supernova remnant around the pulsar. In this model, consecutive bursts (if detected) would have the DM decreasing on a timescale of a few years. The model also provides a natural explanation for the lack of detection at low frequencies (less than ~ 600 MHz): the high density of a young supernova remnant results in the effective free–free absorption at these frequencies [51, 115].

The relatively small distance to the source assumed in this model can also be used as an additional observational test [116]. First, a significant degree of correlation of the FRB positions with nearby galaxies is expected. Presently, the poor FRB localization and their small number do not allow this test to be performed, but estimates show that meaningful results can be obtained with about 100 detections. Second, young neutron stars in this model should be strong X-ray emitters, which could appear as ultra-luminous X-ray sources (ULXs). To verify this hypothesis, a better FRB localization is needed as well.

4.2.2 Magnetars. Shortly after the discovery of the first FRB in 2007, the authors of [114] (see also [117]) put forward the hypothesis that FRBs can be related to hyperflares of magnetars. These hyperflares are powerful short (possibly repeating on timescales of the order of decades or even hundreds of years) episodes of electromagnetic energy release ($\Delta E \sim 10^{44} - 10^{46}$ erg) from the most strongly magnetized neutron stars, magnetars. Magnetar hyperflares are likely related to the catastrophic evolution of a superstrong neutron star magnetic field (up to $B \sim 10^{15}$ G on the surface) in the neutron star magnetosphere (see [118] for a review). First of all, the arguments in [114] were based on the estimated day rate of the magnetar hyperflares of ~ 100 from the local 1 Gpc^3 volume, which is comparable to the FRB statistics. In addition, the temporal characteristics (the sharp increase in the flare profile) are similar in both phenomena. The total energy release in a magnetar hyperflare can also readily explain the observed FRB radio fluxes. A simple scaling of the radio luminosity in one of the models [119] proposed to explain weak magnetar flares yields a good correspondence between the observed FRB fluxes by assuming that the dispersion measure is mainly due to signal propagation in the intergalactic medium. Furthermore, the magnetar hyperflare model easily explains the lack of FRB detections in other bands from distances of ~ 1 Gpc.

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[4] Also see the short comment in [114], where it was noted that a linear scaling of the Crab GPs with spin-down energy losses could explain the FRB properties if a young pulsar has a large, but still realistic, spin-down rate.

A physical model of radio emission generation was not proposed in [114, 117]. In the framework of the magnetar hyperflare scenario, such a model was elaborated in [120]. Later, a similar approach was considered in other papers [121]. In this model, a radio flare is generated by the synchrotron maser mechanism [5] in a relativistic shock arising in a magnetized plasma around a magnetar. For example, this can be an analog of a pulsar wind nebula around the magnetar. Similar nebulae are indeed observed around some magnetars and highly magnetized pulsars [123–126]. In this model, an electromagnetic pulse triggered by a powerful magnetar flare reaches the boundary of the pulsar wind nebula at a distance $r \sim 10^{15} - 10^{16}$ cm. The interaction between the electromagnetic pulse and the nebula gives rise to two shocks (forward and reverse) expanding from the contact discontinuity, and the contact discontinuity itself moves with a Lorentz factor $\gamma_{cd} \sim 10^4$. Behind the front of both forward and reverse (relativistic) shocks propagating in the magnetized plasma of the nebula, an inverse population of electrons with energies below $\gamma_{cd} m_e c^2$ appears, and the conditions for the synchrotron maser radiation from the particles at a frequency of about 1 GHz are satisfied. This frequency is determined by the relativistic cyclotron frequency in the magnetic field behind the shock front, $\sim e B_{EMp}/(\gamma_{cd} m_e c)$ (where $B_{EMp} \sim 10^5$ G is the magnetic field in the electromagnetic pulse in the interaction region). The radio pulse duration W is determined by the time it takes for the electromagnetic pulse energy to be transferred to the pulsar nebula plasma, which turns out to be of the order of the initial electromagnetic pulse width $l/c \sim 10^{-4}$ s.

An important prediction of the model in [120] is the appearance of a simultaneous millisecond hard radiation pulse from the FRB at TeV energies due to the synchrotron radiation of relativistic particles behind the forward shock, which falls into the TeV range in the observer frame. Potentially, ground-based observations with gamma-ray telescopes (HESS, High-Energy Spectroscopic System, MAGIC, Major Atmospheric Gamma-ray Imaging Cherenkov telescope, etc.) can be used to test this prediction. A search for steady TeV emission from the repetitive flashes from FRB 121102 (which, apparently, is a special case) carried out by the VERITAS Cherenkov telescope array gave a null result [71]; the results of synchronous searches for TeV and radio flares from this source have not been published so far.

Unlike the GP model, in the case of synchrotron maser radiation, the time profile of the radio pulse should generally repeat the shape of the initial electromagnetic pulse generated in the course of the magnetosphere restructuring during a giant magnetar flare and should not demonstrate nanosecond substructures. This can also be tested by radio observations with high time resolution.

The short radio flares reported in [127] from the Andromeda nebula (M31) direction might be weaker versions of FRBs. Observations with the WSRT (Westerbork Synthesis Radio Telescope) at a frequency of 328 MHz [127] detected millisecond radio flares with the dispersion measure expected from the distance to M31. In total, several dozen flares were registered. In one case, six flares from one source with a dispersion measure of 54.7 pc cm^{-3} were detected in one hour. Moreover, several other repeating flare candidates

were found. In the magnetar model, weak radio flares can accompany the quasi-regular activity of magnetars, which are sources of repeating soft gamma-ray bursts (SGRs) that can be observed from nearby galaxies [117].

The magnetar model was criticized in [128], in which the authors searched for radio emission from a hyperflare from the galactic magnetar SGR 1806-20. Because the source is located at least four orders of magnitude closer than the potential FRB sources, one could expect to observe a very powerful radio flare that could be detected by the sidelobes of several radio telescopes. The obtained null result reliably suggests that the hyperflare from SGR 1806-20 observed in December 2004 was not accompanied by a radio flare within a wide opening angle (in the magnetar model, FRBs have no emission in a narrow radio beam). This, however, is not a crucial argument, because the conclusion is based on only one source, whose properties can be different. For example, the magnetar SGR 1806-20 is not surrounded by a pulsar wind nebula.

4.3 Fast radio bursts as probes of the intergalactic medium and a tool to test physical and cosmological theories

FRBs are interesting not only in and of themselves but also as a tool for astrophysical and physical studies. In the first place, very short and intense radio bursts are ideal probes for the intergalactic medium. Then, strong bursts at large distances can be interesting for cosmological studies. Besides, short pulses occurring at very large distances offer the opportunity to test predictions of fundamental theories. In this section, we discuss these possibilities.

Applications of FRBs studies of the intergalactic medium have been analyzed in many papers. Usually, such studies assume that the dispersion measure (and also the rotation measure) is mostly due to the intergalactic medium and not to the medium in the host galaxy or in the local vicinity of the source. However, even if the contribution from the intergalactic medium does not dominate and different contributions can be identified, FRBs can still be good probes for the gas and magnetic fields in filaments, voids, and galaxy clusters.

The authors of [129] used the results of numerical modeling of the large-scale structure up to $z = 5$ to estimate the expected values of the dispersion measure and rotation measure and the relative contribution due to different structure elements (filaments, voids, and clusters). It was shown that in the range $0.1 \lesssim z \lesssim 1.5$, the main contribution to the dispersion measure is due to filaments, and at larger distances voids start dominating. The rotation measure is mainly due to galaxy clusters. However, in directions where the line of sight does not cross clusters, it is possible to use FRBs to measure the magnetic field in the filaments.

Data on the dispersion measure of FRBs observed behind galaxy clusters together with the data on the Sunyaev–Zeldovich effect for these clusters were used in [130] to determine parameters of the warm intergalactic medium. Detection of several FRBs behind a cluster might enable the determination of the density profile, and then the Sunyaev–Zeldovich effect can be used to obtain the gas pressure profile. Together, these data would give the temperature profile inside the cluster.

With more FRB statistics, it will be possible to employ them for studies of the intergalactic medium, even without precise individual distance measurements. Such an approach

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[5] The generation conditions for GHz maser radiation in a magnetized relativistic plasma were considered in [127].

is discussed in [131]. However, it is necessary to note that to reach this goal, observations from instruments such as UTMOST, CHIME, HIRAX, and FAST (Five-hundred-meter Aperture Spherical Telescope) most likely could not be sufficient. Only the Square Kilometer Array (SKA) can provide the necessary number of FRBs ($\sim 10,000$).

About 10,000 FRBs will be necessary to put strong constraints on massive compact objects in the galactic halo (MACHO), potential dark matter candidates, via gravitational lensing of these radio bursts [132]. These observations can probe an interesting mass range of MACHOs: 20–100 solar masses, in which the present-day constraints are not strong enough to completely rule out a significant contribution of such objects to dark matter. The time delay during lensing on such objects can be about several milliseconds. Potentially, even smaller delays related to lighter lenses can influence the FRB timing. Recently, the so-called 'nanolensing' of FRBs was discussed in [133]. If observations provide the necessary precision, it will be possible to impose a very strong bound on the number of light compact lenses contributing to dark matter.

Almost immediately after the publication of paper [22], studies appeared with the aim to check whether the FRB statistics are compatible with the assumption about cosmological distances (e.g., [134, 135]) to these sources and whether FRBs can be used as cosmological probes. In [134], a population of FRBs was studied using the numerical modeling of the galaxy distribution and under the assumption that all FRBs are 'standard candles'. Three different models were considered. In the first one, the number of FRBs was assumed to correlate with the total stellar mass (which, for example, corresponds to the neutron star coalescence model). The second model assumed that FRBs are correlated with the star formation rate (in line with models where the FRB sources are related to young objects, for example, active magnetars). Finally, the third model assumed that the FRB phenomenon was somehow linked to the existence of central supermassive black holes in the galactic center. The low statistics make it impossible to distinguish among these three models. In [135], properties of the FRB population were examined assuming their extragalactic origin. Notably, it was shown that with the number of sources available at the time of writing of [135] (as well as at present), no definitive conclusion could be made and several dozen sources are required for reliable studies.

Among papers of the second kind, discussing possible cosmological applications of FRBs, we mention [136–138]. The general conclusion is that FRBs (if they indeed are sources at $z \sim 1$) can be used to estimate global cosmological parameters only with significantly improved statistics and with at least the basic understanding of their properties (e.g., their luminosity function). A recent analysis of prospects for cosmological applications of FRBs can be found in [139]. The results of this study are more pessimistic than previous ones. Nevertheless, the authors conclude that in the future FRBs can be employed to constrain the baryon density of the Universe.

Simultaneous measurements of the DM and z for many FRBs could render them a very effective tool for cosmological studies. This opportunity was studied in [137, 138], where the authors speculate that redshifts can be determined using observations of assumed GRBs associated with FRBs. In particular, this would allow an independent estimate of the baryonic contribution to the total density of the Universe,

and in the case of high-redshift sources, would allow probing the reionization parameters. Several dozen FRBs with known redshifts (if they are distant enough) could be sufficient to constrain some cosmological models. We also mention paper [140], in which the possibility of measuring the proper distances to the sources using a large number (~ 500) of FRBs with known redshifts was analyzed.

Observations of FRBs can be used to determine fundamental physical parameters and to independently test basic physical principles. First and foremost, we mention constraints on the photon mass and tests of the equivalence principle and Lorentz invariance.

Very narrow FRB pulses enable high-precision measurements of the time delay between signals at different frequencies. This offers an opportunity to use the sources for tests of the equivalence principle. For example, in [141], the signal propagation in the galactic gravitational potential was considered. The use of radio data faces the problem of the signal widening due to propagation in the interstellar and intergalactic medium, and this effect cannot be easily separated from the hypothetical time delay due to equivalence principle violation. Hence, it would be important to have simultaneous observations at other wavelengths and/or to obtain an independent estimate of the dispersion measure. Besides propagation in the galactic potential, it is also possible to discuss signals observed behind massive galactic clusters [142]. Modern constraints on the parameter $\Delta\gamma$ (the difference between the post-Newtonian parameter γ at two frequencies) obtained from FRBs are $\mathcal{O}(10^{-8})$ but can easily be improved by more than an order of magnitude with more precise measurements [143].

The first constraints on the photon mass from FRB observations appeared after the claim that the host galaxy of FRB 150418 was identified [144, 145]. Because the identification later turned out to be erroneous, these papers are interesting only from the standpoint of methodology. Only when the repeating source FRB 121102 was robustly identified with its host galaxy and its distance (redshift) was securely measured were interesting constraints on the photon mass obtained [146]: $m_\gamma < 2.2 \times 10^{-14}$ eV, i.e., $< 3.9 \times 10^{-50}$ kg.

5. Conclusions

FRB studies have been carried out for only 10 years. Over this time, many important properties of FRBs have been discovered, including the polarization of radio emission, repeating bursts, and the identification of the host galaxy for the repeating FRB. However, the FRB statistics are growing quite slowly, and the FRB origin remains obscure. Only 'catastrophic' models in which a radio burst is accompanied by powerful radiation in other bands can be rejected at present. Even in this case, the hypothesis that FRBs represent a homogeneous population is required.

Progress in FRB studies may be, first and foremost, related to observations with new sensitive instruments, such as UTMOST, CHIME, and HIRAX. Presently, the new 500 m radio telescope FAST [56] is at the commissioning stage. Calculations show that this instrument will be able to detect about one fast radio burst per week. About the same detection rate is expected in the future from the UTMOST telescope, and the CHIME telescope, according to some estimates, can detect FRBs at an even higher rate (if their number at low frequencies is sufficiently large) [49].

A fantastically high detection rate of one burst per hour is expected from the future SKA (Square Kilometer Array) radio telescope system [147, 148]. However, this is possible only in the distant future.

Presently, successful observations on the Parkes radio telescope continue. Dedicated FRB searches are being carried out by the 300 m Arecibo radio telescope [149]. The new system Realfast, designed to identify short radio transients, will soon be put into operation at the Karl G Jansky VLA radio telescope [150]. In addition, the mounting of the Apertif system [151] at the WSRT radio telescope at Westerbork (Netherlands) will enable this instrument to start actively searching for fast radio transients. It is important to note that this telescope will observe the northern sky, which has not been sufficiently surveyed so far.

It is very likely that as in the case with GRBs, a decisive role in solving the FRB problem will be played by the identification of the events in other electromagnetic bands. This could be done by all-sky gamma-ray observations or optical observations; in the latter case, many hopes are related to the construction of the new-generation Large Synoptic Survey Telescope (LSST) [152].

Methods of quick FRB identification and searches for accompanying transients are being rapidly developed. For example, the project 'Deeper Wider Faster', which includes more than 30 instruments operating at different energy bands, as well as cosmic ray and gravitational wave detectors, is underway [153]. A rapid coordinated real-time exchange of information after detection of an FRB (for example, by the Parkes radio telescope) and extensive preparatory work give hope to obtain important new results in the nearest future.

Anyway, so far, fast cosmic radio bursts that appear each minute in the sky remain one of the most interesting unsolved problems in modern astrophysics.

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