ISSN 1063-7729, Astronomy Reports, 2021, Vol. 65, No. 5, pp. 385–391. © The Author(s), 2021. This article is an open access publication, corrected publication 2021.
Russian Text © The Author(s), 2021, published in Astronomicheskii Zhurnal, 2021, Vol. 98, No. 5, pp. 379–386.

# Neutron Star Mergers and Gamma-Ray Bursts: Stripping Model

**S. I. Blinnikov**[a, b, *], **D. K. Nadyozhin**[a, c, **†], **N. I. Kramarev**[a, d, ***], **and A. V. Yudin**[a, c, ****]

[a] *Alikhanov Institute for Theoretical and Experimental Physics, National Research Center "Kurchatov Institute", Moscow, Russia*
[b] *Kavli IPMU, Tokyo University, Kashiwa (WPI), Japan*
[c] *National Research Center "Kurchatov Institute", Moscow, Russia*
[d] *Moscow State University, Moscow, Russia*
**e-mail: sblinnikov@gmail.com*
***e-mail: nadezhin@itep.ru*
****e-mail: kramarev-nikita@mail.ru*
*****e-mail: yudin@itep.ru*

Received October 27, 2020; revised December 20, 2020; accepted December 30, 2020

**Abstract**—This paper provides an overview of the current state of the stripping model for short gamma-ray bursts. After the historical joint detection of the gravitational wave event GW170817 and the accompanying gamma-ray burst GRB170817A, the relation between short gamma-ray bursts and neutron star mergers has been reliably confirmed. We show that many properties of GRB170817A, which turned out to be peculiar in comparison with other short gamma-ray bursts, are naturally explained in the context of the stripping model, specifically, the time (1.7 s) between the peak of the gravitational wave signal and the detection of the gamma-ray burst, its total isotropic energy, and the parameters of the red and blue components of the accompanying kilonova.

**DOI:** 10.1134/S1063772921050012

## 1. INTRODUCTION

In terms of detection, cosmic gamma-ray bursts are radiation flares lasting from fractions of a second to minutes or even hours. The energies of their radiation lie in the range from tens keV to GeV. Their population is divided into two parts: long and short.

The generally accepted idea is that long gamma-ray bursts are generated during the death of a very massive star, the core of which collapses to form a black hole. The accretion process of the surrounding matter can not only lead to the highly energetic ejection of a significant part of the star's envelope (the so-called hypernova), but also to the formation of narrow collimated ejections of matter (jets). If such a jet is oriented toward us, it will be detected as a long gamma-ray burst.

Short gamma-ray bursts are thought to form during a neutron star (NS) merger, or possibly a NS—black hole merger. This process is usually described using the *merging* model, in which two NSs approach each other through the loss of angular momentum due to the gravitational wave emission and form a single object as a result—a supermassive NS or a black hole. However, there is an alternative to this mechanism, which was proposed in [1], namely, the stripping model. Here, the more massive NS strips off and absorbs the matter of its less massive companion. The latter explodes upon reaching the lower limit of the NS mass, which produces a gamma-ray burst. The now alone and more massive NS (as a result of matter accretion from its companion, it can, in principle, collapse into a black hole) leaves the place of interaction at a significant velocity (up to 1000 km/s).

Event GW170817 is the sixth event detected by the LIGO-Virgo gravitational-wave antennas and the first corresponding to a merger of NSs [2], not black holes. The gamma-ray burst GRB170817A was observed 1.7 s after the signal loss at the GW antennas. This directly confirmed the connection between short gamma-ray bursts and NS mergers for the first time. In addition, this almost simultaneous detection of the GW event and the gamma-ray burst, coupled with the known distance (about 40 Mpc) to the host galaxy NGC 4993, made it possible to impose restrictions on the deviation of the gravity propagation velocity $\nu$ from the speed of light $c$: $|\nu - c|/c \lesssim 10^{-15}$ [3]. Eleven hours later, a visible-light source was also discovered, whose light curves and spectra correspond to the so-called "kilonova" [4]. This confirmed that the gamma-ray burst is accompanied by the synthesis of heavy elements in the r-process. Thus, the first simultaneous observations in gravitational-wave and electromag-

† Deceased.

netic channels marked the beginning of a new era of multi-messenger astronomy [5].

However, the GRB170817A gamma-ray burst turned out to be peculiar; in particular, it was ten thousand times weaker than other weak short gamma-ray bursts with known distances [3]. X-ray and radio observations do not confirm the presence of a strong jet either [6]. At present, theorists try to artificially explain these observations by models of a choked jet, jet cocoon, etc. (see, e.g., [7–9]), where the observation angle of the jet exceeds 13° [10]. The optical observations and the model calculation results of NS mergers also poorly agree with each other [11]. Further, we will show that many properties of event 170817 are naturally explained by the stripping mechanism, as opposed to the generally accepted model of an NS merger.

The plan of this paper is as follows: first, we briefly describe the characteristic features of the merging and stripping models for short gamma-ray bursts; in conclusion, we compare the observational data with the predictions of both models.

## 2. NS MERGER MODEL

Let us consider NSs that form a close binary system. They approach each other due to the angular momentum loss of the system for the gravitational wave emission. The further process is apparently determined mainly by the masses of the system's components. If the masses are sufficiently large, on the order of the solar mass, which is the "standard" NS mass, the merging scenario is realized. At the last stages of NS merging, a non-conservative mass exchange takes place, which is caused by two main processes. In the first process, part of matter is stripped off the NS surfaces by tidal forces and then ejected mainly into the merging plane [12]. The ejected cold and dense neutron-excess matter with an electron fraction $Y_e \lesssim 0.2$ undergoes explosive decompression [13] followed by r-processes, which give a long (approximately a week) transient in the near infrared and optical ranges [14], later called the red kilonova [4]. The other process is associated with the fact that immediately upon the contact of NSs, a part of matter is "squeezed out" into the polar regions. As a result of impact heating, this matter is heated to high temperatures, which leads to an increase in its average electron fraction due to weak interactions [15]. The combined optical and ultraviolet transient generated by radioactive decays in the matter with $Y_e \gtrsim 0.2$ is usually called blue kilonova.[1] The amount of matter ejected in a particular process depends on the equation of state and the NS mass ratio [16].

Depending on the total mass of the binary system and equation of the nuclear matter state, the merging results in a black hole or a rapidly rotating supermassive NS [17], which collapses into a black hole in a time of approximately one second [18], releasing a jet. The newly formed compact object is surrounded by an accretion disk: in the course of nonstationary accretion, a part of the neutron-excess matter spills out, also contributing to the red [19, 20] and blue [21, 22] kilonovae.

Note that in almost all the multidimensional hydrodynamic calculations of the interaction of two NSs at the late stages of the evolution of the binary system, which lead precisely to their *merging*, the NS masses were equal and rather large. Even in a special study devoted to the case of a large mass ratio of binary components [23], the mass of the less massive component was rather large (on the order of the solar mass).

## 3. STRIPPING MODEL AND LNS EXPLOSION

What will change in the scenario described above if the system is highly asymmetric, i.e., the component masses differ significantly, and, moreover, the mass of the low-mass neutron star (LNS) is rather small? Let us consider the details of the process using Fig. 1. Figure 1a shows a binary NS system, in which the component masses satisfy the condition $m_1 > m_2$. At the same time, the LNS ($m_2$) has a larger radius. During the approach, the LNS is the first to overfill its Roche lobe (see Fig. 1b), and through the inner Lagrange point $L_1$, it begins to flow over onto its massive companion $m_1$. In the mass–radius diagram, the stars begin to move in the directions indicated by the arrows in Fig. 1c. For this scenario to be realized, it is important that the initial LNS mass ($m_2$) was on a shallow branch of the NS mass–radius curve (Fig. 1c). The specific value of the LNS mass sufficiently small for the onset of stripping depends on the equation of the NS matter state. In [24, Fig. 1], a set of NS mass–radius curves in the low-mass range for various equations of state is presented. There are significant uncertainties in the behavior of these curves; however, the characteristic value of this mass can be roughly estimated as $M \sim 0.5\ M_{\odot}$.

Let us consider the following aspect of the stripping scenario: will the process of the matter flow be stable? Let a part of the matter $\Delta m$ move from $m_2$ to $m_1$. At the same time, the LNS radius $R_2$ increased (see Fig. 1c). However, the distance $a$ between the components also increased since the system became more asymmetric (a conservative mass exchange is assumed). The effective size of the LNS Roche lobe $R_R$ has also grown. It can be parameterized as

$$R_R = af_R(q), \quad f_R(q) = 0.462\sqrt[3]{\frac{q}{1+q}}, \tag{1}$$

where $q = m_2/m_1 \leq 1$ is the parameter of the asymmetry of the system. The given approximation for $f_R(q)$ is

[1] Note that recently a purple kilonova [4] with $Y_e$ from ~0.2 to 0.35 has also been distinguished.

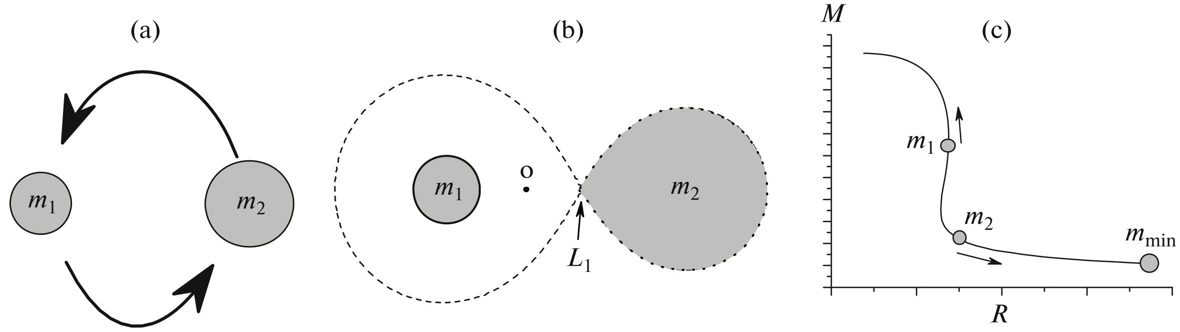


**Fig. 1.** Stripping scenario (schematically): two NSs approach each other due to gravitational emission (a); LNS overfills its Roche lobe and the flow begins (b); as a result, the binary system components $m_1$ and $m_2$ in the mass–radius diagram move in the directions indicated by the arrows (c).

the only possible one; see also [25, 26]. For the stability of the matter flow, it is necessary that $\Delta R_R > \Delta R_2$. This brings us to the following condition:

$$\left|\frac{d\ln m_2}{d\ln R_2}\right| > \left[2(1-q) - (1+q)\frac{d\ln f_R(q)}{d\ln q}\right]^{-1}. \qquad (2)$$

If we use a specific expression from (1) for $f_R(q)$, the expression in square brackets in (2) will be simplified to $5/3 - 2q$. Thus, the flow will be stable as long as the derivative of the LNS mass with respect to its radius (the absolute value) is sufficiently large. As the star $m_2$ loses mass and shifts to the right along the $M-R$ diagram (see Fig. 1c), the $M(R)$ dependence becomes increasingly flat. We used the NS equation of state from [27], and the mass of the massive companion was taken as $m_1 = 1.4\ M_\odot$; it was found that the flow stability is lost when $m_2 \approx 0.107\ M_\odot$. In this case, the minimum NS mass ($m_{\min}$, see Fig. 1c) for this equation of state is $m_{\min} \approx 0.089\ M_\odot$.

Thus, the events in the stripping scenario after the start of the mass exchange unfold as follows: at first, the exchange is stable, i.e., the LNS radius increases more slowly than the critical Roche lobe. The mass exchange takes place on a long time scale, determined by the rate at which the system loses its angular momentum carried away by gravitational radiation. Only when the LNS reaches a very low mass ($0.107\ M_\odot$ in the numerical example above), the stability of the flow is lost, and the remainder of the matter $m_2$ is absorbed by $m_1$ on a fast, hydrodynamic time scale. When $m_2$ reaches the $m_{\min}$ value, i.e., the minimum NS mass, it loses its hydrodynamic stability and explodes. This scenario was first calculated in [28]. The electromagnetic radiation burst accompanying the explosion was proposed by Blinnikov et al. [1] as a source of short gamma-ray bursts. In the subsequent study [29], a hydrodynamic calculation of the explosion process of the LNS that reached the minimum mass was carried out. A comparison of the results with the observations will be given below. The LNS explosion was also considered in a number of studies, which investigated such aspects of the process as the effects of proper rotation [30], the influence of a massive companion on the explosion process [31], the accompanying nucleosynthesis processes [32], neutrino radiation burst [33], etc. [34]. Some historic details of the development of the stripping scenario can also be found in [35].

## 4. COMPARISON WITH OBSERVATIONS

Let us consider the first stage of the stripping scenario, following the study by Clark and Eardley [28]. As a numerical example, they chose a system with initial masses $m_1 = 1.3\ M_\odot$ and $m_2 = 0.8\ M_\odot$. Recall that the maximum $m_2$ value at which stripping is possible depends significantly on the equation of state. If we now compare these masses with the range of masses derived from the analysis of the gravitational wave event GW170817 [36], a fairly close agreement will be found: $m_1 \in (1.36–1.60)\ M_\odot$, $m_2 \in (1.16–1.36)\ M_\odot$ for the case of small proper moments of NS rotation, and $m_1 \in (1.36–1.89)\ M_\odot$, $m_2 \in (1.0–1.36)\ M_\odot$ for the case of large ones (note that earlier [37], the authors indicated a wider range $m_2 \in (0.86–1.36)\ M_\odot$ for the latter case).

NSs approached each other, and the luminosity of the gravitational-wave emission continuously increased until the flow began. After the beginning of the mass exchange, the stars started to "move apart," the asymmetry of the system increased, and the GW luminosity began to decrease. The shape of the GW luminosity curve obtained by Clark and Eardley is remarkably similar to the LIGO-Virgo observations. In 1.7 s after the beginning of stripping (which corresponded to the peak of GW emission), the LNS reached its minimum mass and exploded. In [3, Fig. 2], an astonishing agreement of the measurement results with Clark and Eardley's visionary prediction was demonstrated: after the maximum of the GW emission curve, the LIGO and Virgo antennas lost the signal. And then 1.7 s later, the FERMI and INTEGRAL satellites detected a gamma-ray burst.

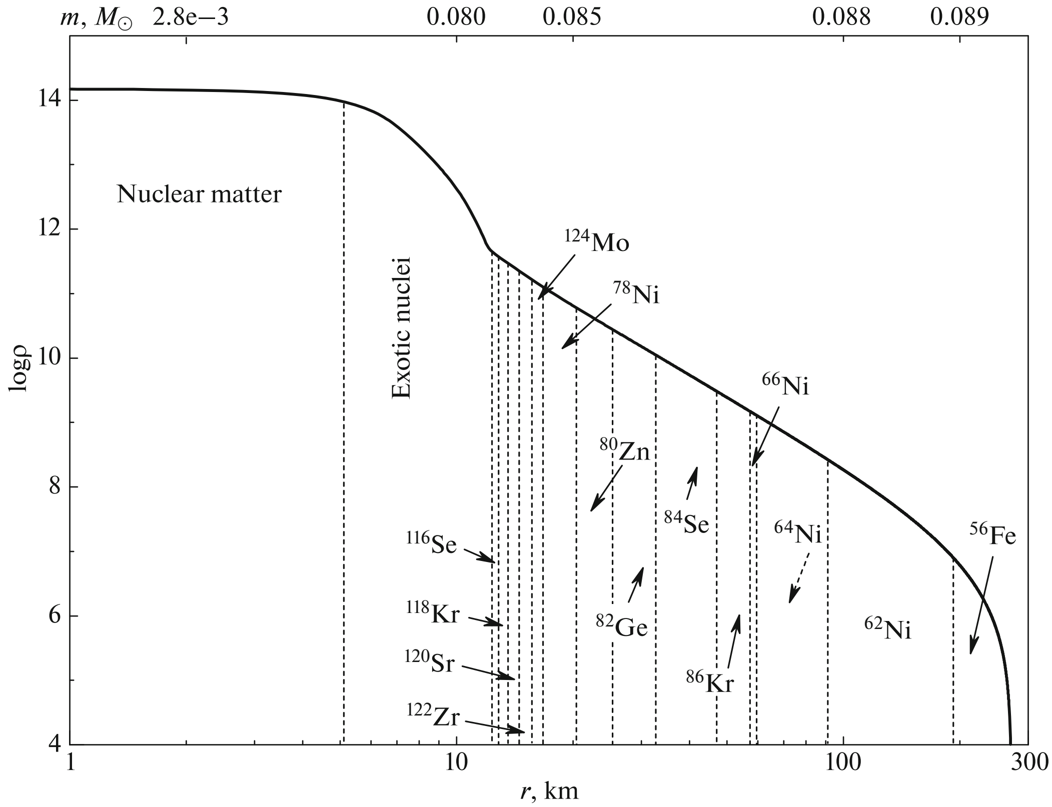


**Fig. 2.** Structure of the minimum-mass LNS. The composition of matter and the dependence of the density logarithm $\log\rho$ on the radial coordinate $r$ are shown. The upper abscissa shows the current mass (in solar masses) for several $r$ values.

Let us now proceed to the key ingredient of the stripping mechanism, the explosion of the LNS in a binary system, and consider the structure of the minimum-mass LNS. Figure 2 shows the dependence of its density logarithm $\log\rho$ versus the radial coordinate $r$. The upper abscissa shows the mass values (in solar masses) for several $r$ values. The structure of matter is also shown: from the surface inward, the outer crust consists of increasingly heavy and neutron-excess nuclei, starting from $^{56}$Fe and ending with $^{116}$Se. The specific sequence and composition of nuclides may vary slightly depending on the mass formula and other parameters of the equation of state for the NS crust (see, e.g., [38]), but the general trend remains the same. Further comes a layer of exotic nuclear structures immersed in a sea of emerging free neutrons; at a density on the order of $\rho \simeq 10^{14}$ g/cm$^3$, this layer turns into a homogeneous nuclear matter. It should be noted that the entire LNS crust extending over 200 km contains less than 10% of the star's total mass. In fact, the LNS consists of a very dense and small (with a radius of approximately 10 km) core, which contains nearly the entire mass of the star, and an extended light envelope.

Let us now consider what happens to the LNS after the stability loss, following the paper [29]. Some details of this process, first calculated by D.K. Nadyozhin in the said study, are shown in Fig. 3. Specifically, it illustrates the dependence of the scattering velocity of the LNS matter $V$ (in km/s) as a function of mass $m$ (in solar masses) inside the star, the so-called "mass" coordinate. The numbers on the curves show the time in seconds after the stability loss. The thick line shows the final value of the expansion rate (the velocity of matter at infinity). It can be observed that the loss of stability and the expansion of matter starts from the surface and covers the entire star in approximately a third of a second. Acoustic vibrations generated at the center propagate along the descending density profile of the extended LNS shell and transform into shock waves (see the velocity surge on the curve at $t = 0.376$ s). In this case, the outer layers are heated to temperatures on the order of $T \sim 10^9$ K. According to the original paper [29]: "This should result in an X-ray and soft gamma ray burst with a total energy of $10^{43}$–$10^{47}$ erg." It was shown in [3, Fig. 4] that the total isotropic energy of the GRB170817A gamma-ray burst was more than 3 orders of magnitude lower than that of other short gamma-ray bursts and amounted to $\sim 3 \times 10^{46}$ erg. Here, we also see remarkable agreement between the stripping model and the observational data. It is also worth noting that the LNS shell consisting of various heavy neutron-rich nuclei (see Fig. 2), which is heated by shock waves and ejected into the surrounding space, is an ideal place for the r-process [32].

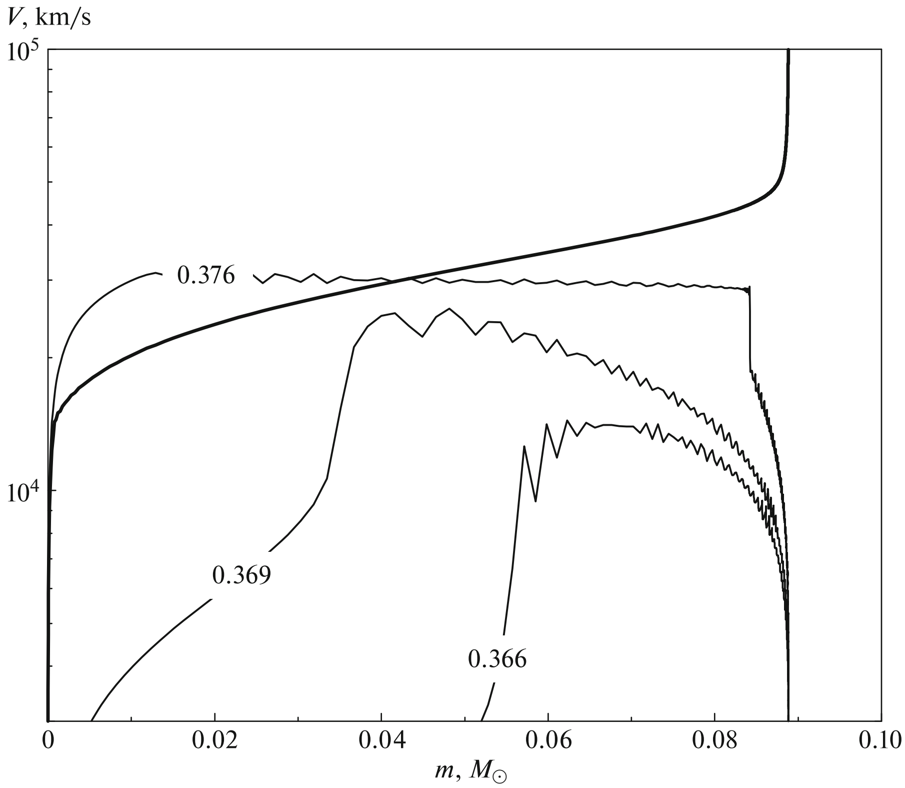


**Fig. 3.** Matter velocity $V$ as a function of mass $m$ in the scattering matter of the LNS. The numbers on the curves show the time (in seconds) after the loss of stability. The thick line shows the final value of the expansion rate.

Let us also refer to the data in Fig. 4 adapted from [11] (reproduced with the kind consent of the author). The figure is a diagram for ejecta mass $M_{ej}(M_\odot)$ versus ejecta velocity $V_{ej}$ (in units of the speed of light $c$) for the matter of the blue and red components of the kilonova, which have the parameters

$$M_{ej}^{blue} = (1.6^{+1.4}_{-0.8})\times 10^{-2}\ M_\odot, \quad V_{ej}^{blue} = (0.27^{+0.03}_{-0.07})c, \quad (3)$$

$$M_{ej}^{red} = (0.5^{+0.5}_{-0.25})\times 10^{-1}\ M_\odot, \quad V_{ej}^{red} = (0.1^{+0.04}_{-0.03})c. \quad (4)$$

Thus, the blue component has a high velocity (about a third of the speed of light) and a small mass of the ejecta, about 1% of $M_\odot$, while the red component, on the contrary, has a low ejecta velocity and a relatively large mass. The symbols on the same graph show the modeling results obtained in the merging model by five different research groups [16, 39–42]. Some of these models can describe the observed parameters of the blue kilonova. However, none of them explains the values typical for the red component of the GRB170817A[2] ejecta. Meanwhile, if we turn to our Fig. 3, we can see that most of the LNS mass (approximately 0.08 $M_\odot$) has velocities on the order of $3\times 10^4$ km/s ~ $0.1c$, and the outermost layers are accelerated to velocities comparable to the speed of light, which fully agrees with the observations.

Another important point focuses on the total kinetic energy of the ejecta. For known short gamma-ray bursts, it is estimated as $E_{kin} \sim 10^{49}$–$10^{50}$ erg (see, e.g., the recent survey [4]). Meanwhile, the characteristic energy $E_{kin} \simeq \frac{M_{ej}V_{ej}^2}{2}$ for GRB170817A, determined using parameters (3) and (4), is $E_{kin} \sim 10^{51}$ erg. However, this is exactly what is given by the stripping model: according to [29], the kinetic energy of the ejecta during the LNS explosion is $E_{kin} \approx 9\times 10^{50}$ erg. The proximity of this energy to the classical energy of a supernova explosion (1 foe = 1 Bethe = $10^{51}$ erg) once led Imshennik to the formulation of his rotational mechanism of supernova explosions [44], in which the LNS explosion is the most important component.

However, in [33], the kinetic energy of the LNS explosion turned out to be lower: on the order of $10^{49}$ erg. This could be due to two factors: first, the authors used the outdated Harrison–Wheeler equation of state, which gave the minimum mass of a NS $M_{min} \approx 0.189\ M_\odot$, i.e., almost double the value pre-

[2] It is worth noting that Siegel [11], from which we borrowed Fig. 4, believes that the parameters of the red kilonova can be explained as the outflow of matter from the accretion disk around the black hole. However, the calculation considering weak interactions [43] disproves this assumption.

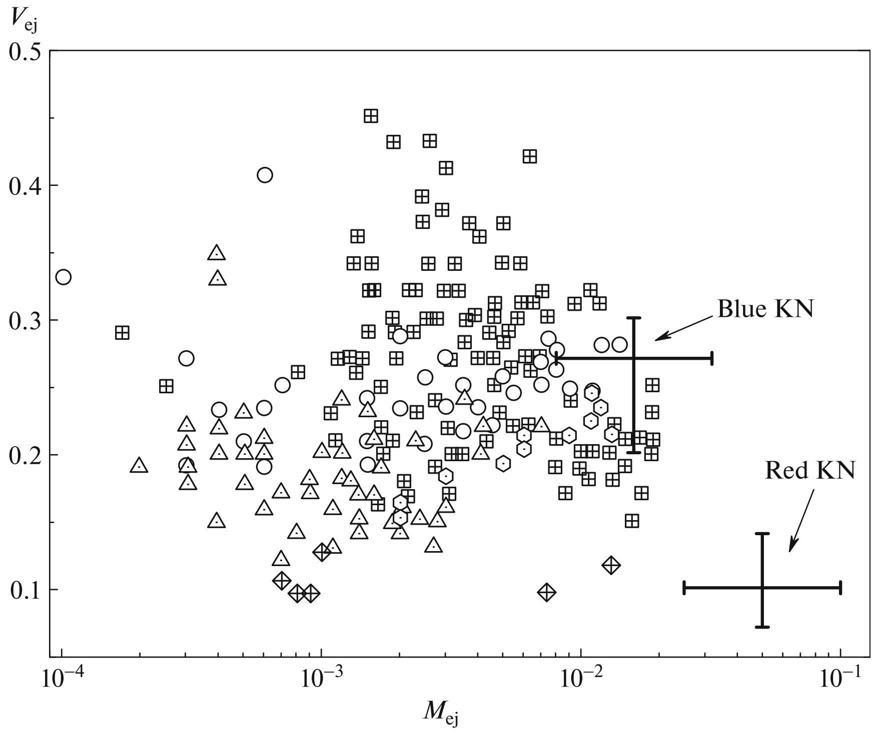


**Fig. 4.** Diagram for ejecta mass $M_{ej}$ ($M_\odot$) versus ejecta velocity $V_{ej}$ ($V_{ej}$ in units of the speed of light) for the blue and red components of the kilonova. The symbols show the results of numerical calculations in various models of NS merging.

dicted by modern equations of state ($M_{min} \approx 0.089\,M_\odot$). From the modern point of view, a NS with such a large mass has negative total energy and cannot explode. Second, the authors of [33] considered the losses due to neutrino emission, although in a greatly simplified formulation of the problem. This loss ingredient is indeed absent in our simulations and can reduce the kinetic energy of the ejection. We are currently working on preparing an appropriate calculation that should clarify this aspect of the problem.

## 5. CONCLUSIONS

In summary, the GRB170817A gamma-ray burst associated with the gravitational-wave event GW170817 confirmed the connection of short gamma-ray bursts with NS mergers. However, many of its properties turned out to be unexpected, if considered in the current paradigm, in which two NSs precisely merge to form a single object. In this case, not a very large amount of matter should be ejected from the system, but part of it can form narrow collimated high-energy jets. Meanwhile, the stripping mechanism provides a natural explanation to the entire set of observational data on GRB170817. Here, we would like to emphasize that one should not make a choice between the merging and stripping mechanisms. Most likely, one process takes place under some conditions, while the other process occurs under others. For the stripping mechanism to be realized, the mass of one of the binary system components should be sufficiently small. However, figuring the specific value of this threshold mass will require significant efforts both in refining the equation of state of NS matter and determining the actual behavior of the NS mass versus radius curves in the low-mass range, as well as calculating the process of mass exchange in the binary NS system, in which one of the components is an LNS. The proportion of binaries with an LNS companion among the entire binary NS population is apparently small. This fraction, which has yet to be determined, will represent the proportion of the stripping mechanism of gamma-ray bursts in their general population. This question is an interesting problem both for observational astronomy and population synthesis [45]. For the second observation of the NS merger, the event GW190425, the accompanying gamma-ray burst was not detected [46]. In terms of the stripping model, this is not surprising: at an estimated distance of about 160 Mpc, the gamma-ray burst in our mechanism is beyond the detection limits (see [3]). On the other hand, the component masses were larger in this case, and, possibly, there was indeed a merger either without a noticeable ejection of matter, or with a jet directed away from us.

## ACKNOWLEDGMENTS

The authors are grateful to the anonymous reviewer for constructive comments.

## FUNDING

The authors are grateful to the Russian Foundation for Basic Research (grant nos. 18-29-21019 MK and 19-52-50014) for the support.



## REFERENCES

1. S. I. Blinnikov, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev, Sov. Astron. Lett. **10**, 177 (1984).
2. B. P. Abbot, R. Abbott, T. D. Abbott, F. Acernese, et al., Astrophys. J. Lett. **848**, L12 (2017).
3. B. P. Abbot, R. Abbott, T. D. Abbott, F. Acernese, et al., Astrophys. J. Lett. **848**, L13 (2017).
4. B. D. Metzger; arXiv: 1910.01617 [astro-ph.HE] (2019).
5. R. Margutti and R. Chornock; arXiv: 2012.04810 [astro-ph.HE] (2020).
6. D. Dobie, D. L. Kaplan, T. Murphy, E. Lenc, et al., Astrophys. J. Lett. **858**, L15 (2018).
7. D. Lazzati, D. López-Camara, M. Cantiello, B. J. Morsony, R. Perna, and J. C. Workman, Astrophys. J. Lett. **848**, L6 (2017).
8. O. Gottlieb, E. Nakar, and T. Piran, Mon. Not. R. Astron. Soc. **473**, 576 (2018).
9. E. Nakar and T. Piran, Mon. Not. R. Astron. Soc. **478**, 407 (2018).
10. D. Finstad, S. De, D. A. Brown, E. Berger, and C. M. Biwer, Astrophys. J. Lett. **860**, L2 (2018).
11. D. M. Siegel, Eur. Phys. J. A **55**, 203 (2019).
12. C. Freiburghaus, S. Rosswog, and F.-K. Thielemann, Astrophys. J. **525**, L121 (1999).
13. J. M. Lattimer, F. Mackie, D. G. Ravenhall, and D. N. Schramm, Astrophys. J. **213**, 225 (1977).
14. L.-X. Li and B. Paczynski, Astrophys. J. **507**, L59 (1998).
15. J. Lippuner and L. F. Roberts, Astrophys. J. **815**, 18 (2015).
16. A. Bauswein, S. Goriely, and H. T. Janka, Astrophys. J. **773**, 78 (2013).
17. J. D. Kaplan, C. D. Ott, E. P. O'Connor, K. Kiuchi, L. Roberts, and M. Duez, Astrophys. J. **790**, 19 (2014).
18. A. Murguia-Berthier, E. Ramirez-Ruiz, F. de Colle, A. Janiuk, S. Rosswog, and W. H. Lee; arXiv: 2007.12245 [astro-ph.HE] (2020).
19. M.-R. Wu, R. Fernandez, G. Martinez-Pinedo, and B. D. Metzger, Mon. Not. R. Astron. Soc. **463**, 2323 (2016).
20. D. M. Siegel and B. D. Metzger, Astrophys. J. **858**, 52 (2018).
21. R. Fernandez and B. D. Metzger, Mon. Not. R. Astron. Soc. **435**, 502 (2013).
22. O. Just, A. Bauswein, R. Ardevol Pulpillo, S. Goriely, and H.-T. Janka, Mon. Not. R. Astron. Soc. **448**, 541 (2015).
23. T. Dietrich, M. Ujevic, W. Tichy, S. Bernuzzi, and B. Brügmann, Phys. Rev. D **95**, 2 (2017).
24. H. Sotani, K. Iida, K. Oyamatsu, and A. Ohnishi, Prog. Theor. Exp. Phys. **2014**, 051E018 (2014).
25. P. P. Eggleton, Astrophys. J. **268**, 368 (1984).
26. D. V. Bisikalo, A. G. Zhilkin, and A. A. Boyarchuk, *Gas Dynamics of Close Binary Stars* (Fizmatlit, Moscow, 2013) [in Russian].
27. P. Haensel and A. Y. Potekhin, Astron. Astrophys. **428**, 191 (2004).
28. J. P. A. Clark and D. M. Eardley, Astrophys. J. **215**, 311 (1977).
29. S. I. Blinnikov, V. S. Imshennik, D. K. Nadyozhin, I. D. Novikov, T. V. Perevodchikova, and A. G. Polnarev, Sov. Astron. **34**, 595 (1990).
30. A. V. Yudin, T. L. Razinkova, and S. I. Blinnikov, Astron. Lett. **45**, 847 (2019).
31. K. V. Manukovskii, Astron. Lett. **36**, 191 (2010).
32. I. V. Panov and A. V. Yudin, Astron. Lett. **46**, 518 (2020).
33. K. Sumiyoshi, S. Yamada, H. Suzuki, and W. Hillebrandt, Astron. Astrophys. **334**, 159 (1998).
34. M. Colpi, S. L. Shapiro, and S. A. Teukolsky, Astrophys. J. **339**, 318 (1989).
35. P. V. Baklanov, S. I. Blinnikov, K. V. Manukovskiy, D. K. Nadezhin, I. V. Panov, V. P. Utrobin, and A. V. Yudin, Phys. Usp. **59**, 796 (2016).
36. B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, et al., Phys. Rev. X **9**, 011001 (2019).
37. B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, et al., Phys. Rev. Lett. **119**, 161101 (2017).
38. S. B. Ruster, M. Hempel, and J. Schaffner-Bielich, Phys. Rev. C **73**, 3 (2006).
39. K. Hotokezaka, K. Kyutoku, M. Tanaka, K. Kiuchi, Y. Sekiguchi, M. Shibata, and S. Wanajo, Astrophys. J. Lett. **778**, L16 (2013).
40. D. Radice, A. Perego, K. Hotokezaka, S. A. Fromm, S. Bernuzzi, and L. F. Roberts; arXiv: 1809.11161 [astro-ph.HE] (2018).
41. Y. Sekiguchi, K. Kiuchi, K. Kyutoku, M. Shibata, and K. Taniguchi, Phys. Rev. D **93**, 124046 (2016).
42. R. Ciolfi, W. Kastaun, B. Giacomazzo, A. Endrizzi, D. M. Siegel, and R. Perna, Phys. Rev. D **95**, 063016 (2017).
43. J. M. Miller, B. R. Ryan, J. C. Dolence, A. Burrows, et al., Phys. Rev. D **100**, 023008 (2019).
44. V. S. Imshennik, Sov. Astron. Lett. **18**, 194 (1992).
45. R. D. Ferdman, P. C. C. Freire, B. B. P. Perera, N. Pol, et al., Nature (London, U. K.) **583**, 211 (2020).
46. B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, et al., Astrophys. J. Lett. **892**, L3 (2020).

*Translated by M. Chubarova*