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Rates and environments of neutron star binaries

Irina Dvorkin

Institut d'Astrophysique de Paris, Sorbonne Université & CNRS, UMR 7095, 98 bis bd Arago, F-75014 Paris, France

Abstract. Recent observations of the various phases in the lives of neutron star binaries across different messengers have led to major discoveries and raised new exciting questions about the environments of these systems. We will overview the current observational constraints on the formation rates and environments of neutron star binaries, as well as theoretical predictions that will be confronted with future observations.

Keywords. stars: neutron, binaries

1. Introduction

Binary neutron stars (BNS) are undoubtedly among the most fascinating astrophysical objects. They allow us to unravel the mysteries of their progenitor stars, the complex binary interactions they undergo along the way, the formation of compact objects and their journey to merger. The observed BNS population is still rather small, as discussed below. However, the rapid development of observational capabilities both in gravitational waves (GW) and radio astronomy will undoubtedly increase this population in the coming years. In particular, the detection of GW from the BNS merger GW170817 and the subsequent identification of its electromagnetic counterparts Abbott et al. (2017a,b) have revolutionized the study of compact binaries.

The interest is studying BNS lies in the diversity of astrophysical processes that come into play. A complete model that describes the evolution of one binary, from formation to merger, needs to account for the evolution of the progenitor stars, their explosions as supernovae (SNe), mass transfer between the stars (which can be stable or unstable), evolution of the orbit and emission of gravitational waves (GW) when the neutron stars (NSs) are close enough. In order to fully describe the *population* of BNS, one needs to take into account their galactic environments, and therefore to include also a description of galaxy evolution.

The population of BNS discussed here consists of 17 binary systems in the Galactic disk that contain at least one radio pulsar; 2 binary systems containing a pulsar that reside in globular clusters; and 2 BNS mergers detected by GW experiments (see Table 1). Clearly, the observed sample is still rather small, but interesting conclusions can already be drawn from its analysis. Moreover, as the observational capabilities of radio telescopes and GW experiments will increase in the coming years, this sample is expected to grow, allowing much more ambitious population studies. There is also hope of additional multi-messenger observations in the coming years, following the spectacular success of GW170817. It is thus of interest to review current theories and to identify the open questions.

This brief overview is structured as follows. First the main formation scenarios are outlined, followed by a description of some observational features of the BNS population,

Table 1. Properties of known BNS systems.

Name	M_1 [$M_\odot$]	M_2 [$M_\odot$]	Time to merger [Myr]	Eccentricity
J0453+1559	1.559	1.174	$1.5 \cdot 10^6$	0.113
J0737-3039	1.338	1.249	86	0.088
J1518+4904	1.41	1.31	$9.2 \cdot 10^6$	0.249
B1534+12	1.333	1.346	2730	0.274
J1753-2240	–	–	–	0.304
J1755-2550	–	> 0.4	–	0.089
J1756-2251	1.341	1.230	1660	0.181
J1811-1736	< 1.64	> 0.93	$1.85 \cdot 10^6$	0.828
J1829+2456	< 1.38	> 1.22	$6 \cdot 10^4$	0.139
J1906+0746	1.291	1.322	309	0.085
J1913+1102	< 1.84	> 1.04	480	0.090
B1913+16	1.440	1.389	301	0.617
J1930-1852	< 1.32	> 1.30	$5.6 \cdot 10^8$	0.399
J1411+2551	< 1.62	> 0.92	$5 \cdot 10^5$	0.17
J0509-3801	1.46	1.34	580	0.586
J1757-1854	1.3384	1.3946	76	0.6
J1946+2052	< 1.3	> 1.2	50	0.06
J1807-2500B	1.366	1.206	–	0.747
B2127+11C	1.358	1.354	–	0.68
GW170817	$1.36 - 2.26$	$0.86 - 1.36$	0	0
GW190425	$1.6 - 2.52$	$1.46 - 1.69$	0	0

Notes:
Data is taken from a compilation by Tauris et al. (2017) and Cameron et al. (2018); Jacoby et al. (2006); Lynch et al. (2012, 2018); Martinez et al. (2017); Stovall et al. (2018) for the Galactic binaries, and from Abbott et al. (2017a); Abbott et al. (2020) for the GW sources.

namely the masses, orbital periods and kick velocities. Merger rates of BNS binaries are discussed next, leading to the question of the host galaxies of these mergers. After a short discussion on kilonovae that accompany BNS mergers the review concludes with some open questions. Short gamma-ray bursts (GRBs), closely related to BNS mergers, are mentioned only in passing in spite of their importance to the subject; this exciting topic is treated in more detail elsewhere in this volume.

2. BNS formation scenarios

The formation of BNS has been extensively studied in recent years, (see e.g. the comprehensive review by (Tauris et al. 2017)). Based on this body of research, the scenario that emerges is that of isolated massive stellar binaries as BNS progenitors. While BNS can also form through dynamical interactions in dense stellar environments, this mechanism is thought to be sub-dominant. A comprehensive comparison of various formation scenarios is given in Mandel & Broekgaarden (2021).

Isolated massive stellar binaries. In the standard scenario (Belczynski et al. 2018; Broekgaarden et al. 2021; Chruslinska et al. 2018; Giacobbo & Mapelli 2018; Kalogera et al. 2007; Portegies Zwart & Yungelson 1998; Tauris, Langer & Podsiadlowski 2015) the formation of a BNS begins with a massive stellar binary and proceeds as follows:

• First SN. The explosion imparts a velocity (birth kick) to the newborn NS, as a result the binary could be disrupted.

• If the binary survives, the system consists of a NS and a massive star (former secondary)

• The envelope of the massive star expands, causing a Roche lobe overflow.

• The systems becomes dynamically unstable, a phase of common envelope follows, during which the NS orbits inside the envelope of its companion.

• The interactions between the envelope and the NS impart energy to the envelope and it is ejected. In some cases the NS may merge with the core of the massive star, in which case no BNS is formed.

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- If the envelope is successfully ejected, the system is that of a NS and a He star.
- Second SN, which imparts another momentum kick to the system.
- If the system survives the second kick, a BNS forms.

The compact binary then loses orbital energy through the emission of GW, and eventually merges. The merger product is a BH, although a metastable NS could also be formed, depending on the equation of state.

Note that the above schematic description does not include additional paths that can have an important effect on the properties of the resulting BNS. One such additional effect is a second episode of Roche-lobe overflow which follows the NS + He star phase. In this case (Tauris et al. 2017) the NS interacts with He envelope of the companion star. When the envelope is ejected, what is left is an almost naked iron core, and the subsequent SN is in this case *ultra-stripped*.

Dynamical formation in dense clusters. An alternative formation scenario can be realized in dense stellar environments (e.g. (Grindlay, Portegies Zwart & McMillan 2006)), where new pairs of compact objects can form, or pair components exchanged. While this process remains a viable formation scenario for binary black holes (e.g. (Rodriguez et al. 2016)), it was shown that it is far less efficient for BNS (Fragione et al. 2019; Ye et al. 2020). Nevertheless, even if the contribution of this process to the total formation rate is negligible, it could produce binaries with peculiar properties, such as highly eccentric short-period systems (Andrews & Mandel 2019).

Population synthesis models. Population synthesis models are a powerful tool that allows to explore populations of (binary) compact objects (Belczynski et al. 2018; Broekgaarden et al. 2021; Chruslinska et al. 2018; Eldridge et al. 2017; Giacobbo & Mapelli 2018; Olejak, Belczynski & Ivanova 2021; Santoliquido et al. 2020). This approach consists of describing the evolution of each star along and off the main sequence, as well as the interactions with the companion star, using a suite of analytic prescriptions. The input is therefore a stellar population, characterized by the masses and chemical compositions of the stars, and the output consists of a series of times at which the identity (type) of each star and the orbital parameters of the binary are saved. This method allows to produce large populations of compact objects and perform comprehensive parameter studies. On the other hand, population synthesis models inevitably involve numerous parameters, some of which are still poorly constrained. Moreover, some of the key processes that come into play in the formation of binary compact object, for example the common envelope evolution phase, are oversimplified. Nevertheless, many predictions of population synthesis models seem to be rather robust, although many important effects need to be further explored to enhance the predictive power of this approach. Among these processes are the strength of stellar winds and their dependence on metallicity; the efficiency of orbital decay during the common envelope phase; and the strength of SN kicks imparted to the newly-born NSs.

3. Masses

Galactic binaries. Galactic binaries can be observed if one of the components is a radio pulsar, and in most cases the masses of both components can be measured (see Table 1). As expected, the masses of first-born (recycled) NSs are slightly higher than second-born (non-recycled) NSs. This difference can be caused by mass accretion of the older NS, but also by differences between the first and second SN.

GW190425 against the Galaxy. BNS masses can also be inferred from GW observations of merging binaries. Among the two BNS binaries detected in GW, the second detection (GW190425) had very unusual total mass of $3.4^{+0.3}_{-0.1} M_{\odot}$, significantly heavier than that of the Galactic binaries (Zhu & Ashton 2020). It is obviously difficult to draw definitive conclusions from a single source, and one possibility is that this is not a BNS but rather

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a neutron star - black hole binary with an unusually light black hole (Barbieri et al. 2020). Nevertheless, assuming GW190425 is indeed a BNS, one may wonder why is this source so different from Galactic binaries. Is it due to some observational biases we do not fully understand, or are there differences in the Galactic vs. the extragalactic populations? One of the reasons for the latter could be the fact that electromagnetic and GW observations target BNS at different stages of their evolution: midlife (for the Galactic binaries) vs. old (for GW systems) as discussed in several studies (Farrow, Zhu & Thrane 2019; Galaudage et al. 2021; Romero-Shaw et al. 2020). If this interpretation is correct, then less massive systems would have longer merger times and would not be observable in GW. Other observational biases may exist and should be explored further, especially when the sample size increases.

Possible connection between masses and merger times. The unusually large masses of GW-detected BNS, if confirmed for a larger sample, could point to a specific formation scenario that favors short merging times of more massive systems. Such a relation could be realized if some systems experience a second episode of Roche-lobe overflow that strips the secondary star of its hydrogen envelope. As a result, the second SN is a so called *ultra-stripped SN* which could preferentially lead to a tighter orbit and therefore shorter merger time, favoring this kind of system as a GW source (Ivanova et al. 2003; Tauris, Langer & Podsiadlowski 2015).

4. Orbital periods and merger time

The distribution of orbital periods at birth determines the merger times of the binaries and therefore the merger rate. Indeed, many of the binaries are expected to have merger times that exceed the Hubble time, and therefore do not contribute to the observed GW signal. Assuming the binary evolves in isolation, its orbit shrinks due to energy loss through the emission of GW. Orbital evolution is determined by the semi-major axis a and the eccentricity e as following (Peters & Mathews 1963):

$$\frac{da}{dt} = \frac{64}{5}\frac{G^3M^2\mu}{c^5a^3(1-e^2)^{7/2}}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) \tag{4.1}$$

$$\frac{de}{dt} = \frac{304}{15}\frac{G^3M^2\mu\, e}{c^5a^4(1-e^2)^{5/2}}\left(1+\frac{121}{304}e^2\right) \tag{4.2}$$

where $M = m_1 + m_2$ is the total mass and $\mu = m_1m_2/M$. The time to merger τ_{GW} can be calculated from the above expressions:

$$\tau_{GW} = \frac{5}{256}\frac{c^5a^4}{G^3M^2\mu}f(e) \tag{4.3}$$

where $f(e)$ is a correction factor due to eccentricity (see (Peters & Mathews 1963)). The time to merger is therefore very sensitive to the initial semi-major axis, but it also depends on eccentricity, eccentric orbits decaying faster than circular ones.

Population synthesis models typically predict a distribution of merger times of $P(\tau_{GW}) \propto \tau_{GW}^{-1}$. This distribution notably contains many binaries with very long delay times. However, Beniamini & Piran (2019) examined the distribution of the merger times of Galactic binaries and concluded that it is inconsistent with the distribution expected from population synthesis models. While population synthesis models are expected to faithfully describe all BNS (Galactic and extragalactic), this discrepancy could point to some inherent differences between the two sub-populations.

One can use the sample of Galactic binaries to try to infer the distribution of orbital parameters and merger times, although the question remains whether these binaries are representative. As can be seen in Fig. 1, no clear correlation between the mass of the

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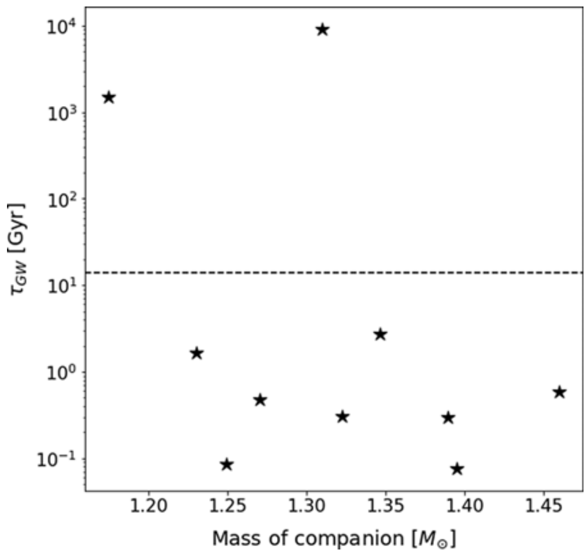

Figure 1. Secondary masses and merger times of Galactic binaries for which mass measurements are available. The horizontal line marks the Hubble time.

secondary component and the merger time emerges from this sample, but the only two systems with merger times exceeding the Hubble time are rather on the low-mass end, and the most massive systems have rather short merging times. Clearly, more data points are needed to establish or rule out such a correlation.

5. Kick velocities

Kick velocities imparted to the remnant after a SN explosion (Andrews & Zezas 2019; Bray & Eldridge 2018; Giacobbo & Mapelli 2018, 2020) can cause a complete disruption of the binary, change the orbital parameters (in particular the eccentricity), or impart a systemic velocity to the binary. Interestingly, in this case the merger will take place far away from the birth site, complicating the association with its host galaxy.

GRB offsets. The strongest evidence in favor of large birth kicks is provided by the observed offset between short GRBs and their host galaxies (Fong & Berger 2013; Troja et al. 2008). Indeed, the association between BNS mergers and short GRBs is now well established, thanks to the spectacular multi-messenger observations of GW170817 (Abbott et al. 2017a). Therefore we can now look at short GRB as a sub-population of BNS. The observed offset is difficult to reconcile with the predictions of population synthesis models, which typically prefer small kicks. In fact, large kicks required to explain GRB offsets would disrupt too many binaries and greatly reduce the expected merger rates.

First vs. second SN. There is some evidence of large differences in kick strength of the first vs. the second SN. Indeed, while the first SN can impart velocities of the order of $O(100)$ km/s, there is some observational evidence that stars on close binaries cause much smaller kicks. This effect could be related to the formation scenario of BNS, where the primary and secondary stars had different evolution paths.

Ultra-stripped and electron capture SNe. The difference between the first and second SN kick could stem from the fact that the second SN is not of the standard kind. Two such classes are ultra-stripped and electron capture SNe (Giacobbo & Mapelli 2018). An ultra-stripped SN occurs when the star is stripped of its hydrogen and helium envelopes.

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The remaining iron core is almost bare, and eventually collapses to produce an ultra-stripped SN with a small amount of mass ejection (De et al. 2018). In this case the explosion will impart a relatively small kick to the remnant, of the order of $O(10)$ km/s.

Dynamical formation. Dynamically assembled BNS in dense stellar environments (e.g. (Grindlay, Portegies Zwart & McMillan 2006)) have lower kicks (~ 50 km/s) and indeed remain bound to their host stellar cluster. However, it seems that this formation channel is subdominant.

6. Merger rates

Observed merger rates. According to GW observations, the BNS merger rates in the local Universe is between $13 - 1900$ Gpc^{-3}yr^{-1} (The LIGO Scientific Collaboration, the Virgo Collaboration & the KAGRA Collaboration 2021). Note that merger rate inferences depend on the presumed mass distribution, and that additional detections will both reduce the statistical error of this measurement and also inform population models.

Constraining formation scenarios. These rate measurements open the possibility to constrain BNS formation scenarios discussed above by using a combination of population synthesis and galaxy evolution models. The realization of this combined description proceeds in general as follows. First a suite of BNS populations are produced using population synthesis codes. These populations are then implemented in galaxy evolution models, either semi-analytic or hydrodynamical, that describe the formation and evolution of galaxies in a cosmological volume. In practice, each *star particle* in cosmological simulation often describes an entire population of stars. This approach, that effectively decouples stellar-size from galaxy-size scales, is quite useful in obtaining realistic population of compact binaries in a cosmological volume. Several such studies have been recently carried out that in general reproduce the observed rate and make predictions for its evolution with redshift (Artale et al. 2019; Briel et al. 2021; Chu, Yu & Lu 2022; Santoliquido et al. 2020). However, this method also poses numerous challenges. First of all, as discussed above, stellar population models rely on many poorly constrained parameters. Some of these parameters may be degenerate with respect to the resulting merger rate. Another difficulty lies in the incomplete description of galactic evolution. One of the key inputs to stellar population synthesis models is the metallicity of the progenitors stars which can strongly affect the strength of stellar winds and hence the mass and even the identity (neutron star or black hole) of the remnant. Unfortunately, different cosmological simulations disagree on the metallicity evolution, and several studies (Briel et al. 2021; Chu, Yu & Lu 2022) recently showed that this discrepancy could affect the predictions for BNS merger rates, even though NS progenitors are less affected by stellar winds than black hole progenitors.

Multiple formation channels. An additional complication may arise from the fact that several formation channels can operate in parallel, and could in the most general case form different sub-populations of BNS. One can then attempt to constrain the branching ratio of each formation channel, as is done for binary black holes. At present it seems that the dominant channel for BNS formation is that of isolated binaries, but this prediction needs to be tested against a larger observational sample.

7. Host galaxies

One of the most exciting questions raised by recent GW observations is the origin of BNS mergers. While GW observations allow us to probe the extragalactic population of BNS, the angular resolution of GW detectors is still quite limited. For example, the 90% credible sky area of GW190425 was 8284 deg^2 (Abbott et al. 2020). Therefore, robust theoretical predictions of the properties (stellar mass, star formation rate, type) of galaxies that could host BNS mergers could greatly help electromagnetic follow-up efforts (Artale et al. 2020; Chu, Yu & Lu 2022; Mandhai et al. 2021).

Cosmological models. The combination of galaxy evolution and population synthesis models discussed above is a natural framework to explore the connection of BNS and their host galaxies. However one of the main uncertain parameters remains the metallicity evolution of the interstellar medium. As mentioned above, these discrepancies lead to differences in the predicted properties of BNS hosts, especially at higher redshift (Briel et al. 2021; Chu, Yu & Lu 2022). It is important therefore to further explore this question, but recent studies already show very promising results. In particular, the properties of BNS host galaxies as predicted by these models seem to be consistent with the host galaxies of short GRBs and kilonovae candidates.

Host galaxy type. The morphology is an important parameter that can help identify potential host galaxies. The host galaxy of GW170817, NGC 4993 (identified through electromagnetic observations), is an elliptical galaxy (Im et al. 2017). However, cosmological models find that BNS mergers seem to prefer spiral galaxies. According to different models, between $\sim 60\%$ and $\sim 80\%$ of BNS mergers occur in spiral galaxies (Chu, Yu & Lu 2022; Mandhai et al. 2021), but this fraction is lower if one considers BNS with long delay times.

Host galaxy stellar mass. The stellar mass is found to strongly correlate with BNS merger rate in cosmological models. According to these studies, most mergers take place preferentially in massive galaxies with stellar masse $M_* > 10^9 M_\odot$ (Artale et al. 2020, 2019; Mapelli et al. 2018; Toffano et al. 2019) and the preferred stellar mass is around $\sim 10^{10} M_\odot$.

Star formation rate. There seems to be a correlation between the star formation rate (SFR) and the BNS merger rate per galaxy, while the preferred SFR is found to be around $2-4 M_\odot \mathrm{yr}^{-1}$ (Chu, Yu & Lu 2022).

8. Kilonovae and r-process elements

The origin of rapid neutron-capture process (r-process) elements, such as gold and europium, is a long-standing question. Indeed, r-process nucleosynthesis, through which about half of all elements above the iron group are produced, requires extreme neutron densities, which can only exist in cataclysmic astrophysical environments.

Kilonovae as the main source of r-process elements. The detection of the kilonova that accompanied GW170817 has provided a direct evidence of the production of heavy r-process elements in BNS merger ejecta (Abbott et al. 2017a,b). The high opacities and the total ejected mass of $\sim 0.05 M_\odot$ inferred from the observed spectral evolution of this event are consistent with model predictions (Kasen et al. 2017). This discovery lends strong support to the idea that kilonovae are the dominant source of r-process elements in the Universe. However, a detailed comparison of the observed abundances with model predictions reveals a more complex picture. As mentioned earlier, population synthesis models generally predict long merger times that are distributed as t^{-1} (where t is the time between binary formation and merger), so that BNS merge several Myr and up to several Gyr after the starburst episode that produced their progenitors. These long time delays are difficult to reconcile with the observations of ultra-metal-poor but r-process-rich stars in the Galactic halo and the Reticulum II and Tucana III ultra-faint dwarf galaxies (Hansen et al. 2017; Ji et al. 2016) which rather seems to suggest a common origin of iron-group and r-process elements in these stars. On the other hand, this observations could point to a population of BNS with very short time delays between formation and merger, which, as discussed above, is favored by certain formation models. Indeed, future multi-messenger BNS detections may provide new constraints on such a fast-merging population as the GRB afterglow should be easier to detect with the denser close environment expected in this case (Duque et al. 2020). A competing hypothesis is that of collapsars or forming magnetars as the dominant source of r-process elements at low metallicities (e.g. Halevi & Mösta 2018; Siegel, Barnes & Metzger 2019). An important factor that needs to be taken into account is the dispersion of newly synthesized r-process matter in the interstellar matter and its mixing in the galaxy (Beniamini & Hotokezaka 2020; Dvorkin et al. 2021).

The effect of kicks. The birth kick imparted to the binary after the second SN would cause the BNS to merge far away (depending on the delay between formation and merger) from its birth site. The r-process elements produced during the merger will therefore be released in a metallicity environment very different from the one the binary itself was born in, which should be taken into account when comparing chemical evolution models to observations.

The effect of BNS masses. The standard assumption is that each BNS merger produced the same amount of r-process material. However, by comparing the kilonova associated to GW170817 and a sample of short GRB afterglow lightcurves, Gompertz et al. (2018) find some evidence for diversity in the emission properties of kilonovae that could not be explained by the viewing angle alone. This could point to differences in the ejected mass. Such a difference could stem from variations in the masses of the binary components.

9. Open questions and outlook

Although the observed BNS sample is quite small, it already poses interesting challenges for theorists. Some of the these questions are:

• *How do BNS form?* Is there a single dominant channel, or do multiple channels contribute to the overall contribution? Specifically, does the dynamical channel have an important contribution? What are the details of the isolated binary channel, for example does the binary undergo several episodes of unstable mass transfer? What is the strength of SN kick velocities?

• *Are there differences between the Galactic and extragalactic populations?* If so what is their origin? Are they due to different formation channels or different observational biases? Does the difference stem from the properties of the host galaxies? Will the Galactic binaries evolve into the kind of systems observable with GW?

• *How do BNS properties depend on environment?* Do BNS properties (masses, orbital separation) depend on the environment in which they were born? What is the effect of the metallicity of progenitor stars?

• *Are BNS merger the dominant source of r-process elements?* Is there a population of fast-merging BNS? How does r-process material disperse in the interstellar medium?

In view of the very limited scope of this review, numerous crucial aspects of BNS physics were completely omitted, even though they are closely related to the topics discussed above. These include notably the SN explosion mechanism (and the related question of the remnant type: neutron star or black hole), the equation of state of neutron stars (that affects the masses) and short GRBs that are associated to BNS merger.

Our understanding of the formation and evolution of binary compact objects, and BNS in particular, has greatly advanced in recent years, thanks both to sophisticated models and new observational results. In particular, GW astronomy and the power of multi-messenger astrophysics have opened a new window into the Universe. Upcoming observations will undoubtedly add additional puzzles but also contribute to an improved theoretical understanding of these exciting systems.

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