To the search for observational evidence of wormholes

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We consider observational properties of gamma-ray bursts (GRB) transmitted by hypothetical wormholes (WH). Such burst would be observable as repeating source, analogous to Soft Gamma-Repeaters (SGR). We show that the known sources of SGR cannot be WH candidates. We also discuss observational properties of GRB which might be a signature of WH.

I. INTRODUCTION

Papers by Kardashev, Novikov, and Shatskiy \([1, 2]\) as well as by Shatskiy \([3]\) deal with a hypothesis that some astrophysical objects (for example, some active galactic nuclei or quasars) are supposedly entrances to wormholes (WH). A wormhole in general relativity is a topological tunnel connecting two distant parts of the universe space (see, for instance, \([4–9]\)) or even two parts of different universes in the Multiverse model \([10]\).

Indeed, if radiation from another universe comes through to our Universe a distant observer will perceive a WH throat as a point source. Both the invariable radiation of the sources of the other universe (stars and galaxies) and the radiation of transient sources will be transmitted to our universe. In the latter the brightest known sources are Gamma-Ray Bursts (GRB). Their brightness in the gamma-rays may exceed for a short time interval that of the entire sky. If GRB phenomena are presumably present in the other universe (the fact that there are GRBs located in distant parts of our universe is undoubted – having been detected up to \(z \sim 8.2\) \([11]\), they are the farthest objects in the Universe which is directly observable now), an observer in our universe will register repeated aperiodic gamma-ray flashes coming from a single point spatially coinciding with a WH.

Such sources with similar properties of repeating radiation do exist. These are Soft
Gamma-ray Repeaters (SGR). Nowadays most known SGRs can be reliably associated with magnetars in the Galaxy (e.g. [12]). However, observational signatures from GRBs of the other universe can still be reminiscent of some properties of SGRs.

In this paper we study possible observational signatures from GRBs of the other universe transmitted by hypothetical wormholes.

II. DERIVATION OF DIFFERENTIAL POWER SPECTRUM (CONTINUOUS APPROACH)

One of few quantitative features we can estimate for GRB transmitted to our universe is the cumulative distribution log \( N(>s) \) – log \( s \), i.e. the number of sources \( N \) with flux exceeding \( s \). The distribution can be referred to as an integral power spectrum (IPS). Hence, a differential power spectrum \( N'(s) \) is related to the integral one through the formula \( N(s) = \int N'(s)ds \).

In Euclidean 3-dimensional space the power law index of the differential power spectrum (DPS) of uniformly distributed identical sources is \( n = -5/2 \):

\[
N'(s) \propto s^{-5/2}
\]

Bright GRBs yield the integral power spectrum index to be \( \sim -3/2 \) (e.g. [13]).

The number \( N'(s) \) is in direct proportion with probability density \( P \) for \( s \) photons to fall onto the WH throat, \( N'(s) \propto P(s) \).

A more straightforward and illustrative way of calculating the spectra is the one that has to do with averaging over all the sources in unit volume and integrating over all the photons emitted by them per time unit. Indeed, in the gamma range where GRBs were first discovered and are currently being detected (30 – 1000 keV) the number of photons emitted by a single GRB is sufficiently large.

However, in the GeV – TeV range where the number of photons emitted by the sources is merely a few we must take advantage of the discrete approach set out in Section III. In the limit of high intensity of source flux the two techniques lead to the same result.

Consider a spherically symmetric case with a wormhole connecting our universe and the other. Let \( 4\pi R^2 \) be the area of the sphere, which an observer rests on, and \( 4\pi r^2 \) be the area of the sphere, which holds a source (of the other universe). Let \( \theta \) be an angle in the
spherical coordinates of the other universe, at which the source is positioned\textsuperscript{1}.

Let \( I \) be the intensity of the source in the other universe. Consequently, the number \( s \) of the photons detected per unit time by the observer in our universe with detector of the surface \( S_1 \) is given by

\[
s = I \cdot \frac{S_0}{4\pi r^2} \cdot f(\theta) \cdot \kappa \cdot \frac{S_1}{4\pi R^2} \quad (2)
\]

Here \( S_0 \equiv 4\pi r_0^2 \) is the effective area of the WH throat surface and \( f(\theta) \) is the deflection function that defines how the apparent brightness of the source detected by the observer (in our universe) changes with angle \( \theta \) (and/or with impact parameter in the throat) while the factor \( \kappa = const \) describes photon losses on passing through the throat. Moreover, since we adopt that the factor \( \kappa \) accounts for the losses, the integral over the entire solid angle \( d\Omega = 2\pi \sin \theta \, d\theta \) with \( f(\theta) \) being the integrand yields \( 4\pi \).

Assume that the sources are identical (\( I = const \)) and uniformly distributed. The mean density\textsuperscript{2} of the sources in the other universe is \( \rho = const \). Let \( \omega = const \) be the average rate of the events per unit volume and time and \( T \) the duration of observation \textsuperscript{3}. According to eq. (2), the condition \( s = const \) defines a surface around the throat, on which holds the relation:

\[
r_s^2(\theta) = \frac{IS_0\kappa S_1}{16\pi^2 R^2} \cdot \frac{f(\theta)}{s} \quad (3)
\]

Then the number \( N \) of detected events with photon number exceeding \( s \) (that came from the entire solid angle of the other universe within the time \( T \)) is given by the integral with respect to volume from the throat to the surface:

\[
N(>s) = \omega T \rho \int_0^\pi 2\pi \sin \theta \, d\theta \int_{r_0}^{r_s(\theta)} r^2 \, dr = \frac{2\pi \omega T \rho}{3} \int_0^\pi \left[ (r_s(\theta))^3 - r_0^3 \right] \sin \theta \, d\theta , \quad (4)
\]

where the function \( r_s(\theta) \) is defined by eq. (3). From the last formula we obtain:

\[
N(>s) = \frac{2\pi \omega T \rho}{3} \left( \frac{IS_0\kappa S_1}{16\pi^2 \rho^2} \right)^{3/2} \int_{-1}^1 f^{3/2}(t) \, dt - \frac{4\pi \omega T \rho r_0^3}{3} = const \cdot s^{-3/2} - const , \quad (5)
\]

\textsuperscript{1} The angle \( \theta = 0 \) corresponds, by definition, to a light ray moving through the center of the throat (the ray with zero impact parameter, see \textsuperscript{14}).

\textsuperscript{2} The averaging is performed over the volume that contains many sources and still much smaller than \( r^3 \).

\textsuperscript{3} The averaging is performed over the time interval \( \tau \) which satisfies the inequality \( 2\pi/\omega << \tau << T \).
where we introduced the substitution $t \equiv \cos \theta$.

And we finally obtain the DPS:

$$\frac{dN}{ds} = \text{const} \cdot s^{-5/2}$$  \hspace{1cm} (6)

This coincides with expression (1), which could be speculated to be true due to the spherical symmetry of the case.

III. DERIVATION OF DIFFERENTIAL POWER SPECTRUM (DISCRETE APPROACH)

After passing through the WH throat the GRB photons will tend to be redistributed inside a solid angle in accordance with equations of papers [14, 15] rather than uniformly.

To begin with, we calculate the probability distribution $P_k^s$ which defines the probability to detect $k$ photons (that reached the observer’s telescope) of the maximal $s$ photons that had been emitted by a GRB and passed through the WH throat. To do so, we apply the following assumptions (see Fig. 1 on p. 4):

1. Let the other universe contain $N_s$ stars of equal luminosity, $N_s \gg 1$.
2. The throat transmits $s$ photons per unit time from every single star.
3. Let the stars be uniformly distributed over the celestial sphere of the other universe.
The observer in our universe looking at the stars in the other universe through the WH throat sees their uneven distribution in the throat. This is because the WH throat deflects and distorts the light of the stars. It is obvious that the distortion will be spherically symmetric and centered around the center of the WH throat.

Now, let the observer look only at the portion of the stars within a thin ring co-axial with the throat, \( h \) and \( dh \) being its radius and thickness. With that the observer examines the solid angle \( d\Omega(h) \) of the other sky, \( d\Omega = 2\pi |\sin \theta| d\theta \). Since the full solid angle equals to \( 4\pi \), in the ring the observer counts \( dN_s = N_s d\Omega/(4\pi) \) stars\(^4\). That is, the apparent density of the stars (the number per unit area of the ring) appears to be \( J = \frac{dN_s}{dS_h} = \frac{N_s}{4\pi} \cdot \frac{d\Omega}{dS_h} \), where \( dS_h = 2\pi h dh \). Since in our model all \( N_s \) stars simulate all possible positions of the identical GRBs (with the number \( s \) of photons that passed through the WH), the value of the apparent star density \( J \) is to be in direct proportion with the sought probability, \( J \propto P^s_s \).

The distortion of light rays that passed through the WH throat is caused not only by redistribution of the apparent star density, but also by the fact that their apparent brightness undergoes a change, viz. the brightness changes with increase of the impact parameter \( h \). This is because increasing the radius \( h \) of the ring, which transmits the starlight, changes a solid-angle element, which the light scatters into. The respective apparent stellar brightness proportional to the number \( k \) of detected photons is in direct proportion with \( \frac{dS_h}{dk} \) and, thus, \( k \propto 1/J \). This yields the sought probability:

\[
P^s_s = \frac{C(s)}{k}
\]

Here the multiplicative factors \( C(s) \) of the probability are defined by the stellar brightness (or the magnitude of a GRB), i.e. by the number \( s \) of GRB photons that passed through the WH. To obtain the factors \( C(s) \) we use the condition of probability normalization:

\[
\sum_{k=1}^{s} P^s_s = C(s) \cdot \sum_{k=1}^{s} \frac{1}{k} = 1 \quad \Rightarrow \quad C(s) = \left( \sum_{k=1}^{s} \frac{1}{k} \right)^{-1}
\]

As \( N_s \to \infty \), the apparent mean brightness of a region within the WH throat is independent of the impact parameter and the wormhole looks like a homogeneous spot in every wavelength range, regardless of a WH model\(^5\).

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\(^4\) Since the light deflection angle \( \theta \) can be more than \( \pi \), the full solid angle turns out to be more than \( 4\pi \). This substitution, however, reduces to another constant (instead of \( 4\pi \)) and does not affect the final result.

\(^5\) As \( N_s \to \infty \), separate stars become unseen – they blur because of the finite resolution of an observing
FIG. 2: Transition from $P^s_k$ to $P^{diff}_k$ as a sum of probabilities of every possible $s$ with weights proportional to $s^{-5/2}$.

According to eq. (1), the set of identical GRBs $j(s)$ (with equal numbers $s$ of photons that passed through the WH) is distributed as follows:

$$j(s) = \text{const} \cdot s^{-5/2}$$  \hspace{1cm} (9)

Therefore, the probability to detect $k$ photons from all $j(s)$ parcels with $s$ photons each is newly re-normalized sum of probabilities:

$$P^j_{k} = \text{const} \cdot \sum_{i=1}^{j(s)} P^s_{k} = \text{const} \cdot s^{-5/2} \cdot C(s)$$ \hspace{1cm} (10)

Thus, the index of the DPS from GRBs, which are equally bright near the WH throat (with the number $j(s) \cdot s$ of photons that passed through the WH and the number $k$ of those of them that reached the detector), is equal to $-1$.

Therefore, the sought-for total probability $P^{diff}_k$ to detect $k$ photons from every possible GRB (with different $s$) is a re-normalized sum of probabilities $P^j_{k}$ for every possible value device. This leads to the averaged overall brightness of the stars being independent of $h$, i.e. the brightness distribution is uniform. On the contrary, if the value of $N_s$ is kept down one can see single stars, i.e. the distribution becomes uneven. Remarkably, this result is universal: it holds for every WH model, provided the total mass of the WH is non-negative.
FIG. 3: Numerical values of the discrete function $n(k)$ giving the DPS for a WH in the range $1 \leq k \leq 10^4$. The deviation of the power law index from $-5/2$ has to do with edge effects near the WH throat and the function $N'(s)$ being singular at zero, see (6).

of $s \geq k$:

$$ P_k^{\text{dif}} = \text{const} \cdot \sum_{s=k}^{\infty} P_k^s = \frac{\text{const}}{k} \cdot \sum_{s=k}^{\infty} \frac{C(s)}{s^{5/2}} $$

(11)

In other words, the total probability $P_k^{\text{dif}}$ is the sum of probabilities $P_k^s$ from every possible GRB with weights, which are in direct proportion with distribution (1) (see Fig. 2 on p. 6).

The DPS index $n(k)$ is given by the expression:

$$ n(k) \equiv \frac{d \ln P_k^{\text{dif}}}{d \ln k} = \frac{k}{P_k^{\text{dif}}} \cdot \frac{d P_k^{\text{dif}}}{dk} $$

(12)
FIG. 4: Numerical values of the discrete IPS function of a WH in the range $1 \leq m \leq 10^3$. The IPS spectral index $n \approx -1.67$.

Using expressions (8), (11) and (12), we can write down the exact expression for the DPS index $n(k)$:

$$-n(k) = 1 + \frac{C(k)}{k^{3/2} \left[ C_1 - \sum_{s=1}^{k-1} s^{-5/2} \cdot C(s) \right]}$$

where $C_1 \equiv \sum_{s=1}^{\infty} \frac{C(s)}{s^{5/2}} \approx 1.193385373682434$ (13)

Figure 3 shows the discrete function $n(k)$ plotted exactly for small values of $k$, for large values $k$: $n \approx -5/2$ - see (6).

In order to obtain the DPS, we merely require to sum up expression (11) with respect to $k$ from $m$ to $\infty$. 
Summing up eq. (11) yields:

\[ P_{m}^{\text{int}} = \text{const} \sum_{k=m}^{\infty} \left( \frac{1}{k} \sum_{s=k}^{\infty} c(s) s^{5/2} \right) = \text{const} \sum_{k=m+1}^{\infty} \left( \frac{1}{k} \sum_{s=k}^{\infty} c(s) s^{5/2} \right) + \frac{\text{const}}{m} \sum_{s=m}^{\infty} c(s) s^{5/2} = P_{m+1}^{\text{int}} + P_{m}^{\text{dif}} \]  

or

\[ P_{m+1}^{\text{int}} = P_{m}^{\text{int}} - \frac{\text{const}}{m} \left[ C_{1} - \sum_{s=1}^{m-1} c(s) s^{5/2} \right] \]  

(15)

Using this recurrent relation it is possible to plot the exact IPS (see Fig. 4).

IV. CAN WE OBSERVE GRB TRANSMITTED BY WORMHOLE?

Suppose that the properties of GRBs in the other universe are analogous to those of GRBs in our universe. The brightest GRBs detected so far provide the flux of \( \sim 10^{-3} \text{erg/(cm}^2 \text{s)} \) in the range \( 30 \div 300 \text{keV} \). On the other hand, the sensitivity threshold of contemporary gamma-ray telescopes is \( \sim 10^{-8} \text{erg/(cm}^2 \text{s)} \) while significantly more sensitive X-ray telescopes can detect fluxes up to \( \sim 10^{-12} \text{erg/(cm}^2 \text{s)} \). Let us estimate the distance \( R \) of the brightest GRB in the other universe, which, on having been transmitted by a WH to our universe, would still be detected.

The flux \( s_2 \) received by an observer on the Earth located at the distance \( R \) from the WH is given by \( s_2 = s_1 \pi R_e^2 / (4 \pi R^2) \), where \( R_e \) is the capture radius of the WH and \( s_1 \) the GRB flux coming onto unit area of the WH throat in the other universe. We also assume that photons losses on passing through the WH vanish. Then, if the capture radius is \( R_e = 4GM/c^2 \) (for the case of the magnetic WH\(^6\)) we obtain \( R = 0.5 \sqrt{s_1/s_2} R_e = \sqrt{s_1/s_2} M/M_\odot 10^{-13} \text{pc} \), where \( M_\odot \) is the solar mass and \( M \) the WH mass. Even with extreme conditions being taken into account (the highest GRB flux, the most sensitive up-to-date detectors (see above) and a supermassive WH, \( M = 10^9 M_\odot \)), we obtain the distance of mere 3 parsecs. It is evident that within a few parsecs from the Earth there are no bodies that massive.

Yet, if the mass of the WH throat in our universe is much lower than that of the WH throat in the other universe, such an object may well be near the Earth (for example, a WH

\(^6\) In the general case we have: \( R_e = \text{min}[r/\sqrt{g_{tt}(r)}] \) — see. 14.
FIG. 5: Differential spectrum \((\log N(s) - \log s)\) of SGR 1900+14. The spectral index is \(n \approx -1.66\). Squares denote BATSE experiment, diamonds – RXTE [16].

...throat could be a single black hole of stellar mass) and observations of GRBs of the other universe (alternatively, a distant part of our own universe) could be possible at the present time.

Besides, lensing may play a significant role. This implies that the deflection function \(f(\theta)\) has maxima in certain directions (angles \(\theta\), in which the apparent brightness of a transmitted source is amplified [14]. If this is the case, observations of GRBs of the other universe can finally be carried out at essentially larger distances between the WH and the observer. In this case, however, no repeating flashes will be detected, since the lensing is realized only for a certain geometry of the system GRB source – WH – observer.

Note the observational properties of a WH in our universe. The WH throat has to be posi-
tioned within a few parsecs from the Earth, manifest itself in the gamma-ray range as a point source of repeating gamma-ray bursts with integral spectrum index \( \log N - \log s \sim -3/2 \), whereas hardness of the repeating gamma-ray bursts and its duration depend on the mass ratio of the WH throats in the other universe and our own realm.

Let us find out whether known soft gamma repeaters suit to be WH candidates. Discovered in 1979 [17], sources of SGR sporadically emit short (\( \sim 0.1 \) s) bursts of soft gamma-radiation with the OTTB spectrum \( \sim E^{-1} \exp(-E/kT) \), where \( kT \sim 20-30 \) keV (e.g. [18]), and, very rarely, giant bursts. The best-known one of the latter was detected from SGR1806-20 in 2004 on the 27th of December [19]. Sources of SGR are currently believed to be magnetars, i.e. single neutron stars with strong magnetic field (\( \sim 10^{13} \div 10^{15} \) G).

Intensity distribution of SGR outbursts was studied, for example, in papers by Gogus et al. [16, 20] (see Fig. 5) where the authors showed that the differential distribution \( \log N(s) - \log s \) for SGR1900+14 is well fit by the power law \( 1.66 \pm 0.13 \) while SGR1806-20 requires the power law index \( 1.43 \pm 0.06, 1.76 \pm 0.17 \) and \( 1.67 \pm 0.15 \) corresponding to the experiments RXTE/PCA, BATSE and ICE, respectively (see also [21]). In both cases of SGR1900+14 and SGR1806-20 the indices within the error bars are inconsistent with \(-5/2\) expected for a GRB transmitted through WH.

Now, let us compare statistics of bursts durations and intervals between them (i.e. waiting time between successive bursts) for SGRs and GRBs. For SGR 1900+14 and SGR 1806-20 the statistics yields typical interval between bursts of 100 s [16] and 50 s [20], respectively, and burst durations of \( \sim 0.16 \) and 0.09 s [22].

The characteristic (most probable) duration \( T_{90} \) in the group of long bursts (\( T_{90} > 2 \) s) is \( \sim 30 \) s [23]. Figure 6 shows the distribution of waiting time between bursts in the BATSE experiment, which along with the analogous distribution for SGRs can be approximated by a log-normal distribution with the most probable value of waiting time being 0.95 days. The ratio of waiting time to event duration is 550 – 630 for SGRs and 3000 for GRBs. When a GRB is transmitted through a WH the ratio of typical duration to waiting time is not to be changed.

Indeed, the waiting time distributions (see Fig. 4) are adequately fit by two log-normal laws (\( \chi^2/d.o.f. = 1.5 \)). Since the field of view of the BATSE experiment is somewhat less than \( 4\pi \), the observed distribution is slightly shifted towards longer times than we would expect from a distribution from the entire sphere. A short-time tail could be caused by
FIG. 6: Waiting time distribution for GRB in the BATSE experiment (histogram), two log-normal curve fitting the distribution (solid), and sum of the curve (dashed). All events from the current BATSE GRB catalogue [27] are used.

including to the catalogue unidentified SGR events as well as by multiple triggering by the same burst, e.g. the precursor and the burst itself or ultra-long GRBs detected as individual events.

As soon as duration and hardness are concerned, note also a contradiction between SGR and GRB spectra. As it is known, most of the observed GRBs are long duration bursts ($T_{90} > 2$ s in the BATSE experiment) and maxima in their spectral energy distribution tend to be 300 keV [29]. On the other hand, SGRs have short durations and very soft spectra. The contradiction could be partially resolved if, for some reason, we observe through WHs only short duration gamma-ray bursts ($T_{90} < 2$ s, and whose durations start from a few milliseconds) forming a separate class of events. But in this case the hardness difference in the spectra turns out to be even sharper than when we compare long GRBs and SGRs.
For some SGRs distance estimates are available, e.g. for SGR1806-20 the distance to the source is estimated to be from 6 to 15 kpc and for SGR1900+14 – 7 kpc. However, it is not the distance estimated rather vaguely that prevents us from associating known SGRs with wormholes. Permanent pulsating radiation with periods ranging from 2 to 8 s demonstrated by most SGRs, which can be easily explained in the magnetar model by rotation of the neutron star, is unlikely to fit the current WH models. One can firmly suggest that known SGRs can not be considered as candidates of wormholes.

The search for recurrent events from classical GRBs was in vain. The most probable candidate could be suspected in 4 successive GRBs with overlapping localization error boxes, which were detected by BATSE in October 1996 (BATSE triggers 5646, 5647, 5648, 5649). However, estimates of probability for these to be actual recurrent bursts are highly dependent of the way the burst durations are interpreted: in the case these events belong to ultra-long GRBs the probability for the mentioned set of events to be recurrent bursts is vanish.

Let us briefly discuss other effects that can arise when a WH transmits a GRB. If the WH connects parts of our universe it is possible to observe the same event twice from two distinct directions. Indeed, one direction is source – observer while the other is WH – observer. Profiles of these events have to be identical within a time scale factor defined by the mass ratio of the WH throats, with the first event being arbitrarily retarded with respect to the second one. Such successive events coming from the same point in space were proposed to be ordinary gravitational lensing candidates.

Indeed, extended literature is devoted to search for GRB with similar light curves (see numerous papers dealing with the search for classical recurrent GRBs and gamma-ray bursts with identical light curves). However there is no any evidence that two or more bursts with similar light curve came from the same source.

V. CONCLUSION

In the paper we have considered a possibility in principle to observe GRBs through a wormhole throat. We have obtained theoretical power spectra and considered observational properties of GRBs transmitted by a WH. Most probably, the transient sources in gamma-ray domain might be candidates in observable wormholes. However at present
time there is no candidates related to GRB transmission by wormhole.

One can guess what precisely are the events that could possibly be identified as WH candidates. These are sources of repeating bursts from the same source that are harder and longer than SGRs. These could also be GRBs with similar light curves however from different localization areas.

In order to observe a gamma-ray burst transmitted through a WH for sure, we need the wormhole to be $1 \div 5$ pc away from the Earth. Alternatively, the gamma-ray burst source could be located near the WH throat in the other universe or in a distant part of our universe. Then observations of WHs are possible at cosmological distances. The candidates could be suspected, in the former case, in GRBs with undetected host galaxies and, in the latter case, in bright gamma-ray bursts with no optical afterglow (so called dark GRB).

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