GW170104 optical counterpart and possible scenarios of gravitational waves generation

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Abstract The gravitational wave event GW170104 detected by aLIGO is of an especial interest for a range of reasons. Firstly, it provides a test on different mechanisms of GW radiation. Besides the most common view on the GW source as a coalescing binary, in this work has been considered the scenario for a core-collapse supernova including a spherically-symmetric one and a massive supernova proposed by Imshennik and Nadezhin. The theoretical predictions have been applied to estimate physical parameters of such objects in order to provide the criteria for the electromagnetic transients search. Secondly, there has been used the proposed by authors method for source localization based on the construction of an apparent circle (AC) on the sky together with the beam pattern to the polarization state of an incoming GW. Interestingly, the AC for GW170104 is perpendicular to the Local Super-Cluster plane with some parts within it. Thus, the predicted positions of the source may belong to the LSC plane, which is consistent with detection of possible optical counterpart ATLAS17aeu.

Keywords: Gravitational Waves, Localization of GW, GW Sources, Optical Counterparts

1. Introduction

Despite the fact that GW radiation was theoretically predicted by A. Einstein as far back as 1916, the question about a practical detection of GWs remained open for decades (Rudenko, V. N. [2017]). The GW radiation should be powerful enough to give amplitude necessary for the detection by the currently working gravitational-waves antennas. Given the current sensitivity of the modern interferometric antennas, the most promising for being detectable are GWs from compact binary coalescence (CBC) and core-collapse supernovae (CCSN). The possibility of detecting waves from each kind of sources depends on the energy radiated in GWs, the distance to the object, the pulse duration and the frequency.

Examining the possible nature of the sources of the LIGO events, there is analyzed the prediction of the existence of scalar wave from a CCSN. Firstly, it is motivated by the possibility of the sinusoidal signal similar to the detected ones, due to spherically symmetric core pulsations. While the tensor waveform by asymmetric collapse is expected to be more complex (see eg., Hawking and Israel [1989], Thorne [1989]). Secondly, as will be shown, the radiated energy as a result of the CCSN is estimated to be orders of magnitude more than ones due to the asymmetric collapse. Consequently, it is possible to detect the GWs from CCSN by the antennas of the current sensitivity ($h \sim 10^{-23}$, LIGO and Virgo) at the distances up to 100 Mpc.

2. Possible sources of GW radiation

Compact binary coalescence (CBC) is a class of GW sources with two relativistic compact objects (hereafter RCOs) on a common orbit. Gravitational radiation during the orbital motion of such objects "takes away" from the system both the energy and the angular momentum, which causes a decrease in orbital radius up to the merger into one RCO. This class of GW sources is of particular interest because the stage of the orbital motion just prior to the merger – the so-called "inspiral" phase can be accurately modeled, which makes the predictions about the waveform and the frequency of a GW signal depending on the masses of the incoming objects. Therefore, observations of CBC can provide us with an excellent test of gravitation theories. In the case of identification of a GW event with its counterpart in the EM branch, it is possible to determine the position of the GW source as well as the distance to it precisely.

Another type of GW events is connected with the explosions of massive supernovae. GW radiation arises as a result of the gravitational collapse of the degenerate core of the star in the late stages of its evolution, resulting in the formation of a compact object such as a neutron star or RCO. In this case, a huge amount of energy is released, of the order of $M_{\odot}c^2$, most of which is carried away by neutrinos and some (still undetermined) portion – by GWs.

An important scenario of the core-collapse of a massive supernova was proposed in the works of Imshennik and Nadezhin (Imshennik [2010]): due to a strong rotation of the core, there firstly occurs the formation of an RCO binary radiating tensor GWs, and then merging into a single RCO with the possible scalar GW radiation.

Although supernovae may be a powerful source of gravitational radiation, up to now there are many uncertainties in the modeling of the collapse mechanism itself. Therefore, it is difficult to make sufficiently reliable assumptions about the amplitude and the waveform of a GW from a supernovae (Thorne [1989], Maggiore [2006], Coccia et al. [2004], Burrows [2013]). Massive supernovae can differ greatly in the nature of the processes occurring in them but for the purposes of GW study, the SN bursts are divided into two types: those resulting from an asymmetric collapse of the core (in the GR) and others as a result of a spherically symmetric core-collapse (in the scalar-tensor theories of gravitation). In addition, the speed of rotation and the presence of a magnetic field should be taken into account. The modern theories of CCSN make it possible to explain the stages of the evolution of a massive star before and after an explosion but there is still no theory that would explain accurately the relativistic collapse stage itself in order to calculate the energy of GW radiation and the observed waveform (see eg. discussion Imshennik [2010], Burrows [2013]). This uncertainty motivates the further studying of the detected GW events from the point of view of the possible origin of such a signal from a collapsing supernova such as CCSN.

The importance of a separate consideration of these types lies in the fact that according to the GR, tensor waves can arise only from an asymmetric collapse (Misner et al. [1973]), whereas both the scalar-tensor metric theories and the FGT predict the existence of a scalar GW mode, which may occur as a result of a spherically-symmetric core-collapse (CCSN) (Novak and Ibanez [2000], Maggiore and Nicolis [2000], Coccia et al. [2004], Maggiore [2006], Baryshev, Yu. V. [1990], Baryshev [2017]).

3. Search for the follow-ups

The detection of transients accompanying a GW signal in the electromagnetic (hereafter EM) branch of the spectrum is of fundamental importance in the analysis of GWs physics.

Firstly, the identification of the detected GW signal with an EM counterpart will increase the confidence that there has occurred a real astrophysical event. Secondly, the joint GW and EM observations complement each other significantly in the understanding of the causing physical processes. The form of a GW signal as well as its frequency, amplitude and polarization state may provide the specific information about the mass motions necessary for the source simulation. While the identification of the GW signal with an EM transient gives it possible to estimate the physical parameters of the environment surrounding the RCO, as well as to localize the source on the sky with the calculation of the distance to it.

According to the GRT, the black holes coalescence in the vacuum does not produce any EM radiation. The same is true for the case of such a merger in the interstellar medium, where the gas density and the magnitude of the magnetic fields are too small to give a noticeable EM "follow-up". However, the RCOs coalescence in clusters, dense molecular clouds and in galactic centers may have some peculiarities in the EM spectrum due to the interaction with gas and magnetic fields.

In the case when a CBC includes at least one neutron star (or an RCO without the events horizon Sokolov and Zharykov [1993], Sokolov [2015], Baryshev [2017]), it can produce the EM radiation in a wide range of wavelengths and on different time scales. Thus, a number of studies has shown (Piran [2004], Nakar [2007]) that there may be expected the short-hard gamma-ray bursts (hereafter SGRBs) with the duration of 2 seconds or less from NS-NS and NS-BH CBCs. In the review (Lipunov and Panchenko [1996]) has been discussed that there may present short radio or optical non-thermal radiation from CBCs including at least one magnetic NS.

Another class of objects expected to give the GW radiation is the CCSN, which may produce the long-soft gamma-ray bursts (LGRBs) (Woosley [1993], MacFadyen and Woosley [1999], Piran [2004]).

4.1. Energy and amplitude estimations for CCSN

According to the theoretical predictions, the tensor GW can be radiated only due to an asymmetric or axisymmetric core-collapse supernova (see eg., Hawking and Israel [1989], Thorne [1989]). However, despite the long-term theoretical study of the gravitational core-collapse of the stars, there is still no reliable estimates of the rate of asymmetry in such processes, which in turn causes uncertainty in the estimates of the radiated energy in the form of GWs.

Thus, studying the dynamics of the asymmetric collapse of the rotating SN core, the authors, Zwerger and Mueller [1997], came to the conclusion that the energy released into the GW is around $E_{\mathrm{GW}} = 10^{-11} - 10^{-8}\ M_{\odot}c^2$, which corresponds to the amplitude of the tensor wave $4 \cdot 10^{-25} \leq h \leq 4 \cdot 10^{-23}$ from the source at the distance 10 Mpc. To a similar result came Bonazzola et al. [1993] for the case of an axisymmetric rotating core with the asymmetry rate $s < 0.1$. On the other hand, examining a fast-rotating core-collapse, Stark and Piran [1985] have given an estimate of the energy radiated in the "+" or "×" polarization mode as $E_{\mathrm{GW}} \leq 10^{-3} M_{\odot}c^2$.

Scalar-tensor metric theories predict apart from tensor waves, the presence of the scalar radiation, which may arise as a result of the spherically-symmetric Core Collapse Supernova (CCSN) (Novak and Ibanez [2000]). In this case, the GW energy is expected to be up to $E_{\mathrm{GW}} \leq 10^{-3}\ M_{\odot}c^2$.

In this way, despite the uncertainty in the explosion mechanism itself, the estimations of the energy emitted in scalar GWs as a result of a spherically-symmetric CCSN are on average by an order of the magnitude higher than such estimations for tensor GWs by an asymmetric or an axisymmetric rotating collapse. In both cases, the duration of a pulsation is estimated to be of the order of 0.5 – 5 ms, the duration of the whole pulse – 1 ms, and the GW frequency is around f ≈ $10^2 – 10^3$ Hz (Zwerger and Mueller [1997]).

A typical GW signal from a CCSN pulsation can be represented as a unit pulse with the amplitude h_0, the frequency f_0 and the total duration τ. There can be estimated the characteristic amplitude of the scalar GW from a typical CCSN burst at the distances at around ~ 1 Mpc, with the duration $\tau = 0.1$ s and emitted during this time the energy $\Delta E_{\mathrm{GW}} = 10^{-3}\, M_{\odot}c^2$ at the frequency f = 100 Hz:

$$h_0^{sc} \approx 1.36 \cdot 10^{-20} \left(\frac{\Delta E}{10^{-3}}\right)^{\frac{1}{2}} \left(\frac{0.1s}{\tau}\right)^{\frac{1}{2}} \left(\frac{100Hz}{f}\right) \left(\frac{1Mpc}{r}\right) \tag{1}$$

While the tensor GW strain (from an asymmetric CCSN) is expected to be approximately 2 times less (see eg., Schutz and Ricci [2010]):

$$h_0^{tens} \approx 6 \cdot 10^{-21} \left(\frac{\Delta E}{10^{-3}}\right)^{\frac{1}{2}} \left(\frac{0.1s}{\tau}\right)^{\frac{1}{2}} \left(\frac{100Hz}{f}\right) \left(\frac{1Mpc}{r}\right) \tag{2}$$

Thus, with the considered parameters, the emitted GW of both kinds of polarization give the strain large enough to be detected by the modern interferometric antennas LIGO, Virgo with the current sensitivity threshold ($h \approx 10^{-23}$, Abbott et al. [2016]).

In contrast to the most common view regarding the mechanism of the CCSN in the frames of GRT and the scalar-tensor metric theories, in the FGT approach (Baryshev [2017]), the upper limit on the radiated in GW energy is established only by the mass of the object itself, which may amount to the several solar masses.

It can be shown that the characteristic amplitude of the scalar wave from a source at the distance of ~ 100 Mpc with the GW energy of the order of several solar masses is:

$$h_0^{sc} \approx 4.34 \cdot 10^{-21} \left(\frac{\Delta E}{M_{\odot}c^2}\right)^{\frac{1}{2}} \left(\frac{0.1s}{\tau}\right)^{\frac{1}{2}} \left(\frac{100Hz}{f}\right) \left(\frac{1Mpc}{r}\right) \tag{3}$$

Thus, the GW from a CCSN at the distance r = 100 Mpc radiating GW with the energy $\Delta E_{\mathrm{GW}} \sim 10^{-2}\, M_{\odot}c^2$ is expected to give the detected strain $h \approx 0.5 \cdot 10^{-21}$.

Comparing the results for the scalar-tensor radiation from CCSN in the frames of both the metric gravitation theories and the FGT, the following conclusion can be made. In contradistinction to the tensor-scalar metric theories, there is no absolute restriction on the radiated into GW energy in the FGT. This allows one to consider the objects as GW sources at farther distances and, consequently, with larger total masses, which might provide corresponding energy on the GW radiation. That in turn establishes the lower limit on the rest mass of the SN collapsing core. Identifying the GW signal as the CCSN, for instance, by the analysis of the follow-up events in the electromagnetic spectrum, the relationship (3) suggests a test for the existence of such objects as supermassive SN. Thus, with the known distance to the object from the EM observations of the transient, and with the detected GW amplitude, it is possible to estimate the energy radiated into GW in the units of solar masses.

Further in this work, there will be given the analysis of the LIGO events in 2015 – 2017 to get estimates on the possible physical parameters of such a CCSN.

4.2. Scalar wave from CCSN in the FGT

As has been discussed, as a result of a spherically-symmetric core-collapse SN, there is predicted the scalar GW radiation (see review Baryshev [2017]). In this case, the expected signal might be in the form of a sinusoidal pulse with the increasing frequency of the pulsations. Further discussion is motivated by the LIGO observations in 2015, which is a fairly correct sinusoidal pulse with the known average frequency and amplitude. In this part will be considered the general relations between the detected values of a GW signal: its "strain" h, (average) period P_0, average frequency f_0, and the physical parameters of the pulsating object: its density P_0, radius R_0, as well as the distance r to the object.

For a CCSN with the characteristic period of the pulsations $P_0 \sim 1/f_0 \sim 1/\sqrt{G\rho_{eff}}$ (Baryshev, Yu. V. [1990]), there can be determined the effective density ρ_{eff} taking into account the inhomogeneity of the mass distribution along the radius of the object:

$$\rho_{eff} \sim \frac{1}{P_0^2 G} \tag{4}$$

Let us introduce the parameter characterizing the relationship between the effective density ρ_{eff} and the average density $\rho_0 = M_0 \left(\frac{4}{3}\pi R_0^3\right)$, where R_0 is the radius of the object, and M_0 – its (average) mass.

$$\gamma = \frac{\rho_{eff}}{\rho_0} \tag{5}$$

The next parameters can be introduced: α characterizing the pulsations velocity $v_0 \sim R_0/P_0$ relative to the speed of light c, and β – for the ratio of the average radius R_0 of the object to its gravitational radius R_G:

$$\alpha = \frac{v_0}{c} \tag{6a}$$

$$\beta = \frac{R_0}{R_G} \tag{6b}$$

The compatibility condition for the entered parameters can be written as:

$$\frac{\gamma}{\beta} = \frac{4}{3}\pi\alpha^2 \tag{7}$$

which means that the relationship γ/β can be determined by the known or estimated parameter α. The parameter limiting conditions: $0 \leq \alpha \leq 1$; $0 \leq \gamma \leq 1$; $\beta \geq 1$ are presented in ***Fig1***.

The amplitude of a GW at the distance r from the source can be obtained as:

$$h_0 \sim \frac{R_G}{r}\alpha^2 \tag{8}$$

where $R_G = GM_0/c^2$ is the gravitational radius of the collapsing core.

Using the derived above relationships, there can be represented the relation "the distance to the object r – the registered strain h" in the form depending only on the observed period of the pulsations P_0 and the parameter of the changing rate α:

$$h_0 \sim \frac{4}{3}\pi c \cdot \frac{P_0}{r} \cdot \alpha^5 \sim c \cdot \frac{P_0}{r} \cdot \frac{\gamma}{\beta} \cdot \alpha^3 \quad (9)$$

Thereby, with the observed data h, P_0 and an supposed GW energy ΔE_{GW}, there can be estimated (9) the introduced source parameters α, β, γ connected by the compatibility condition (7). Which give the estimates of the radius R0, mass M_0 and density ρ_0 of the CCSN.

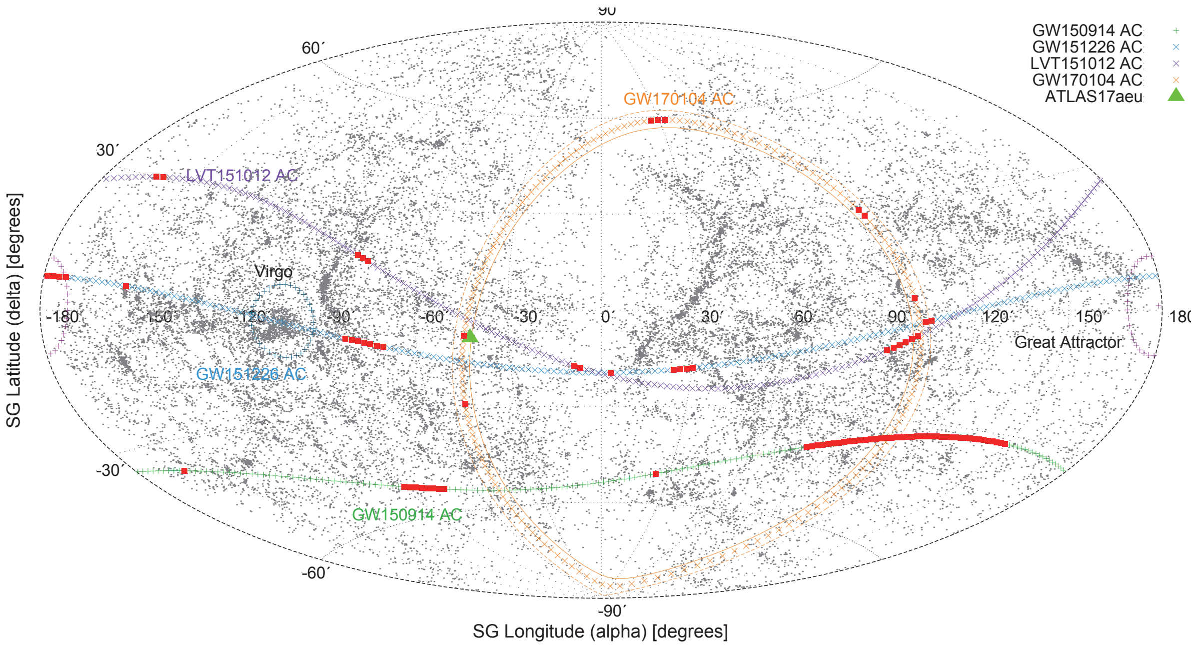

Fig1. *Possible localization of a GW source along the ACs for the LIGO event GW170104, in the supergalactic CS. The red points corresponding to the condition $G_l/G_H \approx 1 \pm$ 20% represent the allowed source positions in the case of the mixed tensor polarization state ($G = 1.5F_+ + \sqrt{2}\, F_\times$) of the incoming GW calculated by the method (Fesik et al. [2017]). The green triangle marks the position of the possible transient ATLAS17aeu.*

5. Analysis of GW events detected by LIGO in 2015 – 2017

5.1. GW event from Core-Collapse Supernova

According to the considered above approaches to the study of a CCSN, metric and field, there is established a different limit on the radiated into GWs energy. Thus, according to the scalar- tensor metric theories, this limit is estimated to be $\Delta E_{\mathrm{GW}} \leq 10^{-3} M_\odot c^2$, while in the FGT, the amount of the radiated energy is limited only by the rest mass of a collapsing, which can amount several solar masses. In this connection, it can be shown what difference is expected in the parameters of a CCSN radiating GWs of different energy, with a frequency and amplitude similar to those detected by LIGO in 2015.

The calculations have been made using formulae (1) for scalar and (2) for tensor GW mode, which illustrate the dependence of the GW amplitude h0 on the distance to the object r for a typical CCSN with radiated GW energy of the order $\Delta E_{\mathrm{GW}} = 10^{-3} M_\odot c^2$, according to the discussed above the estimates of the maximal energy possible to be radiated in GWs in the frames of the scalar-tensor metric theories. Besides this, there has been done the calculation for a scalar wave from spherically-symmetric CCSN with the radiation energy $\Delta E_{\mathrm{GW}} = 1 M_\odot c^2$, which is possible in the frame of the FGT.

Table 1. *Calculated parameters for a CCSN under the condition that the detected GW signal has average frequency f = 100 Hz.* r_1 *is the distance to the object corresponding to the detected strain h =* $0.6 \cdot 10^{-21}$ *(GW150914),* r_2 *– to the case of h =* $0.25 \cdot 10^{-21}$ *(GW170104). Mass of the Sun* $M_\Theta \approx 2 \cdot 10^{33}$ *g, the gravitational radius* $R_G = GM_0/c^2$*, and the assumed parameter* $\gamma = \rho_{eff}/\rho_0 \equiv 1$ *gives the effective density* $\rho_{eff} = 0.15 \cdot 10^{12}$ *g/cm*^{3}*.*

ΔE [$M_\Theta c^2$]	r_1 [Mpc]	r_2 [Mpc]	v_0/c	R_0/R_G	M_0/M_Θ
10^{-6}	0.72	1.74	0.06	58.44	2.22
10^{-3}	22.88	54.92	0.13	14.68	17.64
1	723.57	1736.57	0.35	3.69	140.08

The average data of the GW signals detected by LIGO in 2015{2017: frequency f_0 = 100 Hz, pulse duration τ = 0.1 s. As has been mentioned, with the same detected strain, the GW with higher energy will come from a more distant object. There can be estimated the parameters of a CCSN at such distances, radiating a scalar GW with an average period $P_0 = 1/f_0$ = 0.01 s. The relationship for a CCSN (9) give the parameter $\alpha = v_0/c$ as well as the parameter ratio γ/β (7). The results for typical values of radiated energy: $\Delta E_{\mathrm{GW}} = 10^{-6}$; 10^{-3}; 1 $M_\Theta c^2$ are given in the Table1. The calculations have been made for the average detected strain values: $h = 0.6 \cdot 10^{-21}$ (GW150914) $h = 0.25 \cdot 10^{-21}$ (GW170104), with the assumed $\gamma \equiv 1$, i.e. $\rho_0 = \rho_{\mathrm{eff}} = 0.15 \cdot 10^{12}$ g/cm^3. For these amplitude values, there are no strong differences in the CCSN parameters but the estimated distances to the objects are clearly different: denoted by r_1 and r_2 respectively.

There should be noted that these calculations are model and use average values of the detection parameters without taking into account the variation with the time. To sum up, a CCSN radiating GW with the energy of the order of the solar mass should have a high pulsation rate, a radius close to the gravitational one, and a mass close to the extreme estimates for a massive pre-star of the CCSN, to give a signal with the detected amplitude.

6. Localization for GW170104. Possible transient ATLAS17aeu

In this section, we will discuss an optical event discovered by the ATLAS team to be a follow-up for the GW event GW170104 detected by LIGO on 1 January 2017 at 10:11:59 UTC (Abbott et al. 2017). The alert for the counterparts search was reported 6.6 hours later.

The ATLAS is the Asteroid Terrestrial-impact Last Alert System (Stalder et al., 2017) specializing in the near- Earth survey of asteroids. The ATLAS uses the follow-ups search program Pan-STARRS Smartt et al. [2016]. The ATLAS system comprises two half-meter wide-field telescopes, of which at that time only the Haleakala telescope in the Hawaiian archipelago was in operation.

The observations by the ATLAS team were conducted targeting the fields of the GW170104 localization provided by LIGO. This is the banana shaped skymap with coordinates from RA=108:79, DEC=7:662 to RA=170:55, DEC=72:314 (Fig. 1 in Stalder et al., 2017).

23 hours after the registration of the GW170104, a bright optical transient was detected – ATLAS17aeu – with a rapid decrease in luminosity during the next 2 hours, at the coordinates RA=138.30789, DEC=+61.09267 (09:13:13.89, +61:05:33.6). Besides optics, the ATLAS17aeu was observed in the x-ray by the team Swift (Evans et al. 2017b), as well

as in radio – by the AMI (Arcminute MicroKelvin Imager; Mooley et al. 2017) and the VLA (Very Large Array; Corsi et al. 2017).

In addition, independently of these observations, a gamma burst GRB170105 was discovered by the POLAR group (Marcinkowski et al., 2017), also observed by several satellite missions: AstroSat CZTI (Sharma et al. 2017), Konus-Wind, INTEGRAL SPI-ACS (Svinkin et al. 2017). This gamma burst is considered to be a "long-soft" with the redshift $1 \leq z \leq 2.9$. However, both the localization of this burst and its detection time differ from the localization and time of the optical ATLAS17aeu, which indicates the different origin of their sources.

To sum up, at the present time there is considered the possibility that two astrophysical events: the GW170104 and the optical ATLAS17aeu, both occurred during the day and being spatially close, originate from the same source.

Concerning the nature of the source of this GW event, there is adopted a version about a coalescing binary (CBC) being the most probable source, which may give a quasi-sinusoidal signal similar to the detected by LIGO. Thus, within the framework of the GR, it is assumed that the source of the GW170104 is the CBC BH-BH (comprising two black holes) with masses $20 - 50M_{\odot}$, which are obtained by the analysis of the waveform and frequency of the signal. However, taking into account the field approach to the theory of gravity (the FGT), such masses may belong to RCOs without events horizons, which may provide a sufficient amount of matter to generate the observed optical transient ATLAS17aeu.

It can be noted that in the case of tensor radiation from a source such as a CBC, a combination of tensor modes "+" and "×" is expected to observe. In particular, for tensor waves with some variation of weight coefficients, there is predicted a region of a source localization calculated by the method Fesik et al. [2017], which matches with the position of the possible transient ATLAS17aeu, Fig1.

Besides this, within the framework of the FGT, a possible interpretation of the detected pulsating GW signal is also the existence of a scalar GW with a quasi-sinusoidal waveform from the spherically-symmetric CCSN (Ch. 4). Therefore, considering the localization regions that depend on the assumed polarization state of the GW (Fesik et al. [2017]), it is necessary to take into account the results for both tensor and scalar modes.

Using the method Fesik et al. [2017], there were constructed apparent circles together with the possible localization for the cases of the scalar and the tensor "plus" modes in the supergalactic (SG) CS, taking into account the error in the measurement of the time delay between the signal receiving 3 ± 0.5 ms (see Table1). It should be noted that the coordinates of the optical event ATLAS17aeu are within the SG plane, which is consistent with such an interpretation of the nature of this event as a CCSN in the local super-cluster of galaxies (LSC) at the distances 100 Mpc. The corresponding projections of the positions of galaxies from the 2MRS catalogue are plotted on the map. However, the calculated localization region with the observed strains ratio $h_L/h_H \approx 1 \pm 20\%$ for the assumed scalar polarization mode is located away from the position of the ATLAS17ae, ***Fig. 1***. For the concrete coordinates of the ATLAS17aeu, the method predicts the strains ratio to be $h_L/h_H \approx G_L/G_H = 19.0$.

7. Conclusions

Within the framework of the General Relativity, there exists only tensor GW radiation, which can occur as a result of a compact binary coalescence (CBC) or an asymmetric core-collapse supernova (CCSN). Analyzing the waveform of the LIGO signals in 2015 – 2017, there has been made the conclusion about the nature of all these sources being CBCs.

For such a system, with the registered signal parameters, there can be drawn sufficiently reliable conclusions about the size of the system, the masses of the incoming bodies, the distances to it, and the GW energies. Thus, in the case of the GW150914, the distance to the generating CBC is estimated to be ~ 440 Mpc. An important test of the model of a CBC is the identification of a detected GW event with the optical and X-ray transients, which are possible only in the case of the coalescence of RCOs without the events horizon, which is possible within the frame of the field theory of gravity ("gravidynamics").

In the frame of GTR modifications (the scalar-tensor metric theories), as well as in the field approach to describing gravity (the FGT), there is predicted the existence of scalar GW radiation from a spherically-symmetric pulsating core (CCSN), with the waveform expected to be close to a sinusoidal with a varying frequency similar to the waveform from a CBC. The principal difference between the predictions of the metric theories based on the GR and the FGT is the limit for the radiated in GWs energy. According to the scalar-tensor metric theories, there is presupposed the GW energy radiated from a CCSN to have a limit of $\sim 10^{-3} M_{\odot} c^2$, while the FGT makes the limitation on the radiated energy only by the rest mass of the collapsing SN core itself.

The carried out in this paper evaluations for the scenarios of scalar wave radiation as a result of a CCSN from the point of view of the metric theories and in the FGT approach showed that at the same recorded wave amplitude but at different limiting energies, the sources should be at different distances and have different internal characteristics such as mass, radius and kinetic energy of pulsations. The observational test of the existence of spherically-symmetric pulsations in the core of supermassive SNs will be the identification of the GW event with the associated SN counterpart in the electromagnetic spectrum. This also will allow us to estimate the distance to the object and, as a consequence, the limits of the mass and density of the object.

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