Gravitation theory in multimessenger astronomy II: crucial observational tests based on GW and optical observations

Yu.V. Baryshev[1], S.A. Oschepkov[2]

[1]Astronomical Department, Saint Petersburg State University, Saint-Petersburg, Russia;
yubaryshevl@mail.ru

[2]Taurida Academy, V.I. Vernadsky Crimean Federal University, Simferopol, Russia

Abstract Multimessenger astronomy provides crucial observational tests of gravity physics for two alternative theories of gravitation – Einstein's geometrical General Relativity Theory (GRT) and Feynman's non-metric field gravitation theory (FGT), which we considered in the first report. Such tests are able to clarify the key question on the nature of gravitational interaction: is gravity the curvature of space? or is gravity a material field in Minkowski flat space as other physical forces? Up to now all actually performed experiments/observations do not allow to distinguish between these two alternatives in gravity physics, however forthcoming multimessenger astronomy will bring the answer to this fundamental question.

Keywords: relativistic astrophysics, gravitation, observational tests, relativistic compact objects.

1. Introduction

Multimessenger astronomy deals with all four fundamental physical forces – strong, weak, electromagnetic and gravitational interactions. The corresponding messenger particles - cosmic rays, neutrinos, photons and gravitons (gravitational waves), provide crucial information on the most violent phenomena in the Universe. Simultaneous study of these particles may help us answer fundamental questions in high-energy astrophysics, including the nature of massive supernova explosions, gamma-ray busts, active galactic nuclei and relativistic jets. Especially important fact is that the nature of all these phenomena is based on the gravitation theory.

Hence multimessenger astronomy provides crucial observational tests of gravity physics for two alternative theories of gravitation – Einstein's geometrical General Relativity Theory (GRT) and Feynman's non-metric field gravitation theory (FGT). Basic initial principles, field equations and the equations of motions for these alternative theories of gravitation (GRT and FGT) have been given in our first report "Gravitation theory in multimessenger astronomy I: comparison of geometrical and field approaches to the physics of gravitational interaction". In this part we discuss differences in interpretation of some astrophysical observations when one uses GRT or FGT.

2. Crucial observational tests

2.1 Localization of Gravitational Waves which carry positive energy

Recently gravitational-wave signals were detected by using Advanced LIGO and Virgo interferometric antennas (Abbott B. et al. [1], [2]). This means that the positive gravitational field energy carried by gravitational waves, was localized by a GW detector, i.e. free gravitational field energy can be transformed to the kinetic energy of the moving LIGO mirrors. An interpretation of the GW detector length variations as a contracting and stretching the "space-time" without energy taking from gravitational wave is a nonphysical approach.

Though it is possible in the frame of GRT to introduce non-covariant description of GW energy-momentum (Maggiore 2008 [3]), however it leads to some conceptual problems because of giving up the general covariance principle in geometrical description of the gravitational field energy. Indeed, according to Landau & Lifshitz 1971 [4] (§101, p.307): "...it has no meaning to speak of a definite localization of the energy of the gravitational field in space..." and "so that it is meaningless to talk of wether or not there is gravitational energy at a given place". Also according to Misner, Thorne & Wheeler 1973 [5] (§20.4, p.467): "...gravitational energy... is not localizable. The equivalence principle forbids", and (§35.7, p.955): "...the stress-energy carried by gravitational waves cannot be localized inside a wavelength" and "...one can say that a certain amount of stress-energy is contained in a given 'macroscopic' region of several wavelengths' size".

In part I we have described the equations of scalar and tensor gravitational radiation in FGT. The equations corresponds to the radiation of two types – pure tensor gravitons (traceless, spin-2) and scalar gravitons (trace of the tensor potential, spin-0). In the frame of FGT the generation of scalar wave can be calculated by using retarded potentials, which give in the case of the wave zone approximation the following expression:

$$\psi(\boldsymbol{r},t) \approx \frac{2GM_0}{r} - \frac{2GE_k}{rc^2} + \frac{2GM_0}{r\,c}\left(\boldsymbol{n}\cdot\dot{\boldsymbol{R}}\right) + \frac{G}{r\,c^2}\,n_\alpha n_\beta \ddot{I}_{\alpha\beta} + \cdots \,, \tag{1}$$

where $M_0 = \Sigma\, m_a$, $E_k = ½\, \Sigma\, m_a\, v_a^{\,2}$, $\boldsymbol{R} = \Sigma\, m_a r_a / \Sigma\, m_a$, $I_{\alpha\beta} = \Sigma\, m_a\, x_a^{\,\alpha}\, x_a^{\,\beta}$.

Taking derivative of (1) over time (at fixed point r) and excluding non-contributing terms, we get following equation for the time derivative of the scalar potential:

$$\dot{\psi}(\boldsymbol{r},t) = -\frac{2\,G\,\dot{E}_k}{r\,c^2} \tag{2}$$

It means that the scalar gravitational radiation is the second order monopole radiation, and there is no first order monopole, dipole and quadrupole scalar radiation. Using the expression (2) for the energy density in the scalar wave, we get

$$T^{00}_{(g)\{0\}} = \frac{G\,\dot{E}_k^2}{8\pi c^6 r^2} \tag{3}$$

The energy flux is $cT^{00}_{\{0\}}$, so the additional loss of energy (in 4π steradian) due to the scalar monopole radiation is

$$L_{\{0\}} = \frac{G}{2c^5}\,\dot{E}_k^2 \tag{4}$$

so the scalar gravitational (actually "anti-gravitational") radiation has the same order $1/c^5$ as the tensor of quadrupole radiation.

The test for correctness of gravitational radiation formulas is a double systems of a pulsars. For a binary system the loss of energy due to the pure tensor gravitational radiation is given by the quadrupole luminosity (which is the same in FGT and GRT)

$$L_{\{2\}FG} = \frac{G}{45c^5}\,\dddot{D}^2_{ab} \tag{5}$$

where $D_{\alpha\beta}$ is the quadrupole moment of the system. We note that tensor gravitational wave in the frame of FGT is transversal and has localizable positive energy.

For a binary system the quadrupole luminosity is

$$< \dot{E} >_{\{2\}} = \frac{32G^4\, m_1^2 m_2^2\,(m_1+m_2)(1+\frac{73}{24}e^2+\frac{37}{96}e^4)}{5c^5 a^5 (1-e^2)^{7/2}} \tag{6}$$

here m_1, m_2 are masses of the two stars, a is the semimajor axis and e is the eccentricity of the relative orbit.

For a binary star system the orbital additional energy loss via scalar waves (according to Eq.(4)) is

$$< \dot{E} >_{\{0\}} = \frac{G^4\, m_1^2 m_2^2\,(m_1+m_2)(\,e^2+\frac{1}{4}e^4)}{4c^5 a^5 (1-e^2)^{7/2}} \tag{7}$$

Hence the ratio of the scalar to tensor luminosity is

$$\frac{<\dot{E}>_{\{0\}}}{<\dot{E}>_{\{2\}}} = \frac{5}{128}\cdot\frac{(\,e^2+\frac{1}{4}e^4)}{(1+\frac{73}{24}e^2+\frac{37}{96}e^4)} \tag{8}$$

The value of this ratio lies in interval 0 - 1.1% depending on the value of the eccentricity e, and for a circular orbit equals zero. Note that for PSR1913+16 binary pulsar the observer excess of the energy loss is (+0.848 +/-0.041)%, while the FGT prediction for additional scalar radiation is +0.735% (see discussion in [11]).

However, for a spherically-symmetric pulsating body the radiation of the scalar gravitational field becomes dominating because quadrupole radiation is absent.

2.2 Existence of Black Holes event horizon and singularity.

There are several paradoxes related to the concept of black hole horizon, which were emphasized by Einstein 1939 [6]. Einstein wrote in [6] - "Schwarzschild singularity cannot exist in physical reality". The information paradox was recently discussed by Hawking 2014 [7] and the incompatibility of classical and quantum concepts of the BH horizon was considered by Chowdhury & Krauss 2014 [8]. The infinite time formation of the classical BH event horizon (in the distant observer's coordinates) and finite time of BH quantum evaporation means that a BH should evaporate before its formation ([8]). Stephen Hawking claimed in [7] that "There would be no event horizons and no firewalls. The absence of event horizons mean that there are no black holes - in the sense of regimes from which light can't escape to infinity". Though there is no escape from a black hole in classical theory, but in quantum theory, energy and information can escape from a black hole. It means that an explanation of the gravity physics requires a theory that successfully merges gravity with the quantum fields of other fundamental forces of nature.

In FGT there is no black holes, horizons and singularities, and no such limit as the

Oppenheimer-Volkoff mass (review in [11]). This means that compact massive objects in binary star systems and active galactic nuclei are good candidates for testing GRT and FGT theories. According to FGT for a static weak field conditions the positive energy density of the gravitational field around an object with mass M and radius R is

$$\varepsilon_g = \frac{(\nabla\varphi_N)^2}{8\pi G} = \frac{GM^2}{8\pi r^4} \tag{9}$$

It is positive, localizable, and does not depend on a choice of the coordinate system.

A very general mass-energy argument shows that in FGT there is the limiting radius of any self-gravitating body and there is no singularities. This argument is a precise analogue to that of the classical radius of electron. Indeed, the total mass-energy of the gravitational field existing around a body is given by

$$E_{field} = \int_{R_0}^{\infty} \frac{(\nabla\varphi_N)^2}{8\pi G} 4\pi r^2 \, dr = \frac{GM^2}{2R_0} \tag{10}$$

This energy should be less than the rest mass-energy of the body, which includes the energy of the gravity field. From this condition it follows that:

$$E_{field} < Mc^2 \quad => \quad R_0 > \frac{G\,M}{2\,c^2} \tag{11}$$

If one takes into account the non-linearity of the gravity field and the internal energy-part inside the object, then the value of the limiting radius further increases, because "the energy of the field energy" should be added. As the gravitational radius Rg for any massive body in the field gravity we define the radius, where mass-energy of the gravitational field equals to half of its mass-energy measured at infinity, so:

$$R_g = \frac{G\,M}{c^2} = \frac{1}{2} R_{Sch} \tag{12}$$

Recent surprising observational fact [13] is that the estimated radius of the inner edge (Rin) of the accretion disk (around black hole candidates has sizes about (1.2−1.4)R_g = (0.6−0.7)R_{Sch} points to a suggestion, that instead of a Kerr BH rotating with velocity about 0.998c, we observe ordinary RCO having radius close to its limiting FGT value R_g (Eq.12).

Also VLBI observations, using submm wavelength Event Horizon Telescope (EHT), have unique angular resolution which will achieve event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre (SgrA*) and M87. The first results of EHT observations at 1.3mm surprisingly has demonstrated that for the RCO in SgrA* there are no expected for BH the light ring at radius $5.2R_{Sch}$ ([9], [10], [14]). Again this may points to a possibility the existence of limiting FGT RCO having finite gravity force at its surface which does not produce light rings. So in the frame of FGT there is prediction, that forthcoming EHT observations at 0.6 mm will discover a combination of radiation from a central RCO, accretion disc and the origin of relativistic jet from the surface of the RCO (without black hole horizon in the center energy source).

2.3 Relativistic Compact Objects.

Observations of the stellar mass BH candidates surprisingly discovered a preferred value of RCO mass about 7 $M_\odot$ ([15], [16]). Intriguingly in the frame of Quantum Gravidynamics (which is extension of FGT into the strong field regime) a quantum consideration of the macroscopic limiting high density quark-gluon bag gives self-gravitating configurations with preferred mass 6.7 $M_{\odot}$ and radius 10 km [16]. So, quantum gravidynamics predicts two peaks in mass distribution of the stellar-mass relativistic compact objects: 1.4$M_{\odot}$ for neutron stars and 6.7$M_{\odot}$ for quark stars.

In the weak field regime the post-Newtonian equation of hydrostatic equilibrium of a spherically symmetric body in FGT is:

$$\frac{dp}{dr} = -\frac{G(\rho_0+\delta\rho)M_r^*}{r^2} \tag{13}$$

where

$$\delta\rho = \frac{e+p}{c^2} + 2\rho_0\frac{\Phi}{c^2}\ , \tag{14}$$

and

$$M_r^* = \int_0^r 4\pi r'^{\,2}\left(\rho_0 + \frac{e+3p}{c^2} + 2\frac{\rho_0\,\Phi}{c^2} + \frac{(d\Phi/dr)^2}{8\pi G c^2}\right) dr' \tag{15}$$

The most important difference of the Eq.(13) of hydrostatic equilibrium in FGT is that the Tolman-Oppenheimer-Volkoff equation in GRT has the form:

$$\frac{dp}{dr} = -\frac{G\left(\rho+\frac{p}{c^2}\right)(M+4\pi p r^3/c^2)}{r^2\,(1-r_{Sch}/r)} \tag{16}$$

According to the Tolman-Oppenheimer-Volkoff equation the factor $1/(1-r_{Sch}/r)$ leads to an infinite pressure gradient for $r \to r_{Sch}$. This has a deep consequence: there is an upper limit for the mass of static compact relativistic stars, around 2 - 3 $M_{\odot}$. According to the standard GR compact objects with larger masses may exist only as black holes.

According to FGT the relativistic gravity corrections lead to a decrease of the gravitating mass (and so gravitational force) relative to its Newtonian value (due to the negative value of the gravitational potential ($\Phi = \psi^{00} < 0$)). According to Eq.(13) a hydrostatic configuration is possible for any large mass. Another important prediction of the FGT is that the supermassive stars (suggested as a possible source of energy in quasars) are stable to small adiabatic pulsations [17]. Whereas the first calculations in FTG on the equation (13) give extreme masses of 5 - 6 $M_{\odot}$ for EOS FPS and SLy4.

3. Conclusion

Decisive role of optical observations in multimessenger astronomy relates to the very large potential informativity of classical spectral analysis. Especially localization and identification of the GW sources can solve the riddle of the nature of the gravitational interaction.

The crucial astrophysical phenomena for testing Einstein's geometrical General Relativity Theory (GRT) and Feynman's non-metric field gravitation theory (FGT) are ([11],[12],[15],[16]):

- The additional acceleration in translational motion of rotating bodies (according to FGT is~ $\mathbf{V^2_{rot} / c^2}$)should be tested in orbital motion of binary neutron stars;
- The scalar-tensor nature of symmetric tensor potentials $\boldsymbol{\psi^{ik}(r,t)}$, $\boldsymbol{\psi(r,t) = \eta_{ik}\ \psi^{ik}}$

(repulsion by the trace part of the symmetric tensor) will change the structure, masses and sizes of Relativistic Compact Objects (Neutron Stars, Quark Stars and Super Massive RCO having radiuses $\mathbf{r \sim R_g = GM/c^2 = R_{Sch}/2}$) and origin their relativistic jets;

- The emission of gravitational waves of spin 2 and spin 0 during massive supernovae explosion and GRB events, and detection these GWs by means of interferometric antennas (in FGT energy density of gravitational waves: $\mathbf{T_{\{2\}}^{00}}$ and $\mathbf{T_{\{0\}}^{00}}$ is positive and localizable).

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