Measurement Techniques, Vol. 43, No. 9, 2000

FUNDAMENTAL PROBLEMS OF METROLOGY

CLASSIFICATION OF GRAVITATIONAL-WAVE ANTENNAS BY THE METHODS OF GRAVITATIONAL RADIATION DETECTION

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UDC 530.12

A gravitational-wave antenna classification according to known methods of gravitational radiation detection is proposed for the first time. Underlying the classification is the principle of spatial formation of the measuring channel, i.e., on the Earth's surface, in near space, within the solar system, and on cosmological scales.

The possible existence of gravitational waves was predicted by Einstein in his work [1], which was devoted to the solution of the equations of the general theory of relativity and calculation of the power of gravitational radiation. Calculations showed that the distance between test bodies changes very little under the action of a gravitational wave. This is why the problem of detecting gravitational radiation remained an object of theoretical investigation for a long time.

The existence of gravitational radiation was confirmed by experimental studies of the effect of the period of the binary star system PSR 1913+16 being slowed down by the loss of energy for gravitational radiation [2, 3]. The results from processing experimental data agreed with the calculated values obtained by solving the equations of the general theory of relativity, with a high degree of accuracy. Subsequently various gravitational radiation detection methods have been presented, many of which have not been implemented either because the method is not sufficiently sensitive or because it is too complicated technically to carry out. A fairly large number of publications have been devoted to the development of new gravitational-wave (GW) detection methods, improvement of known methods, the study of various factors that affect the sensitivity and noise immunity of gravitational-wave antennas (GW antennas). The results of some studies can be used both in ground-based and space GW antennas.

The investigations done on the optimization of parameters by the methods of signal isolation, antenna orientation, and the functioning of their circuits are fairly general and may not contain new GW detection methods. Concealed in this is an ambiguity associated with the construction of new GW detection methods for obtaining fundamentally new information on existing GW antenna schemes. Consideration of new GW detection methods may lead to new requirements for the conditions or parameters of devices, which are basically unfeasible.

Clearly, the aforementioned difficulties do not permit a final version of the classification of the proposed GW detection methods to be made. The development of such a classification, however, might allow the detection methods to be separated from methods of higher sensitivity and noise immunity, allow the latter to be extended to GW antennas of various classes, and would point out possible gaps in the use of known actual phenomena for constructing desired measuring procedures. Below we attempt to construct the most general classification of GW detection methods.

This classification is based on the principle of the spatial formation of a measuring channel: on the earth's surface, in near space, within the solar system, and on cosmological scales. Thus earth-based, space, and astronomical GW antennas can be distinguished.

Earth-based GW antennas detect gravitational waves in devices or systems of devices located on the Earth's surface. The best-known are resonant, rotational, and free-mass GW antennas.

Resonant GW antennas were the first made and they detected unidentified signals, close in shape to the expected GW bursts. Weber [4] reported the observation of agreement between the readings of two detectors, one of which at Maryland University and the other in the Argonne National Laboratory, 1000 km away.

Translated from Izmeritel'naya Tekhnika, No. 9, pp. 21–25, September, 2000.

Underlying the method is the interaction of a gravitational wave with a normal mode of a solid-state cavity, which is made as a massive high-Q cylinder with a sensor reacting to the oscillations of the cylinder. Such antennas were developed in the 1980’s at CERN [5], the M. V. Lomonosov Moscow State University [6], and other scientific centers. The antennas must be cooled to ultralow temperatures to decrease the thermal noise and the dimensions of the antennas must be increased for better interaction of the GW with the cylinder, but technical considerations limit its length to 2 m. The sensitivity of such antennas reached 10^{-18}–10^{-19} arb. units [7, 8]. The current problems of the given detection method include the influence of electronic signal-processing systems on the cylinder oscillations sensor, decreasing the thermal noise [9], and eliminating the effect of cosmic rays [10].

Resonant GW antennas also include the Tokyo University disk antennas [11, 12], which are square parallelepipeds which have four through cuts or holes and react to the perturbation of the quadrupole oscillation mode. In the given GW antenna, two opposite sides of the square oscillate in phase with each other but opposite in phase with the other two sides. A distinctive feature is that they can detect GWs in the low-frequency range to frequencies of the order of 60 Hz. As a development of this method of GW detection, we can consider the proposal for constructing GW antennas with a spherical design [13] that would allow a large cross section and, therefore, efficient conversion of GW energy into acoustic oscillations.

At present, the resonance method has a sensitivity close to the theoretical attainable value, i.e., 10^{-20}–10^{-21} arb. units, but stable GW signals have not yet been detected. In future, GW antennas could work effectively in a grid of gravitational-wave antennas in a prolonged signal acquisition mode [14].

In a rotational GW antenna, DW detection by an oscillator is possible if the acceleration field induced by the GW is in phase with the antenna rotation. This low-frequency, resonance method has been used at the University of Tokyo [15, 16]. The antenna was tuned to 60 Hz and theoretically can detect continuous radiation at a level of 10^{-23} arb. units. The problems inherent to this method include rotation frequency instability, as well as the influence of low-frequency noise that cannot be eliminated.

Detection of low-frequency GWs based on processing of signals from seismographs on one block of the earth’s crust was proposed in [17, 18]. A gravitational wave leads to correlated excitation of the opposite ends of the block of the earth’s crust and this should allow the GW to be discriminated against the background of the seismic noise. The requirements of this method include a high Q and linear characteristics over the large dynamic range of the seismographs incorporated into the network.

The method of electromagnetic wave modulation in a circular waveguide by the action of a GW can be associated with the electromagnetic version of a rotational GW antenna [19–21]. Modulation occurs at the combination frequencies of the electromagnetic wave frequency and the frequency of the gravitational radiation frequency. This method is for a high-frequency region of the order of 1 MHz, but has not been implemented technically.

A number of publications proposed that the superconducting state of a material be used for DW detection [22, 23]. In a superconducting cylinder, the action of a gravitational wave induces a potential difference between the centers of mass of the cylinder and its end. Accordingly, using the theoretical limit of voltage resolution 10^{-22} V, we can record signal amplitude variations of 10^{-22} V and such variations of 10^{-24} arb. units can be recorded for a cylinder 3 m long. Clearly, in this method the problems entailed in obtaining a superconducting state and recording limiting voltage variations are added to the problems of an ordinary Weber GW antenna.

A method was also proposed for detecting GWs by measuring the capacitance between electrically conducting materials. An induction current arises when a closed circuit, with a capacitance, is biased in an external electromagnetic field [24]. A compact GW source is necessary, however, if the actions on the measuring and external circuits are to differ.

One GW detection method uses a circuit with two capacitors that are perpendicular to each other and parallel to the GW front and are combined into a closed circuit [25]. The idea behind that method is that the GW-induced charge should flow from one capacitor to the other. Extracting a current of the order of 10 pA over a period of four months, the method can detect GWs with an amplitude of 10^{-24} arb. units.

Among the methods that use particle accelerators, we single out the method of GW detection by the action of a quadrupole, which is formed in 10^{-23} sec in an electron-positron collision, on another quadrupole – a mass oscillator [26].

Tamello [27] described the effect of gravitational radiation pressure and analyzed the possibilities for intensifying it. Sazhin [28] examined the possibility of laboratory detection of low-frequency GWs, using the cumulative effect when gravitational radiation acts on the photon frequency shift. Callagari [29] proposed using the Mossbauer effect for GW detection. The methods of [27, 28] are methodological, for the most part, since their technical implementation has not been analyzed sufficiently.

We note a number of methods using nonlinear optical processes that can effectively intensify the action. In the first group of those methods, the nonlinear optical process reacting to the GW takes place within the laser cavity. In [30], Danileiko proposed the use of competitive nonlinear resonances in ring lasers. The second group includes methods whose sensitivity to gravitational radiation is obtained by introducing nonlinear optical elements into the GW antenna scheme. In particular, Iacopini [31] proposed that use be made of the birefringence that appears in an optical crystal when deformed in the field of a GW.

Khizhnyakov [32] suggests GW detection by ultranarrow dip in the radiation spectrum of a whisker, when the oscillations of a test body are transferred to the whisker and are detected by the change in transparency of the latter at the frequency of the dip. Kulagin and Rudenko [33] also proposed that a nonlinear optical crystal be used in an interferometric GW antenna.

A method of GW detection described by Braginsky and Torne [34, 35] is based on the memory effect in a free-mass GW antenna, that effect being that after several cycles of oscillations the GW spike decreases to a certain level, not to zero. This effect can be obtained by time integration of the signal.

A number of methods is based on the idea of GW energy being pumped into electromagnetic energy as the GW propagates along an electromagnetic wave. That idea was discussed by Teissier [36] for the Hertz experiment and by Akishin et al. [37] for a microwave periodic structure. The method remains purely theoretical, however, because of the low energy pumping coefficient.

In recent years, preference has been given to multibeam interferometry methods for the detection of gravitational radiation because of theoretical and experimental research on various physical principles. The use of optical interferometry with coherent optical pumping for GW detection was first proposed by Gertsenshtein and Pustovoit [38].

Construction of a high-sensitivity laser interference gravitational-wave antenna (LIGA) with a baseline of the order of several kilometers is under way in some foreign scientific centers [39]. Some of the projects are based on a Michelson interferometer, the arms of which contain conveniently tunable Fabry–Perot cavities (FPCs) with a low level of scattered light and optical resonance properties [40, 41].

The salient features of the calculation of the Fabry–Perot interferometer response in GW detection stem from the extremely small amplitude of the expected GW signals, which should be caused by small variations of the separation of the cavity mirrors. In a number of experiments, estimates were made of the upper limit of the amplitude of cosmic GWs [42, 43], which impose limitations on the amplitude of the expected displacement of the Fabry–Perot cavity mirrors; those displacements are of the order of 10^{-15} m for cavities with kilometer dimensions [44, 45]. To reduce the influence of vibrations and noise factors of a seismic origin, the Fabry–Perot cavity mirrors are placed on test masses, which are loosely connected to the base. This results in new effects due to the laser radiation pressure on the Fabry–Perot cavity mirrors.

The requirements that GW antennas be more sensitive have stimulated the development of new optical methods of detection of ultrasmall mirror displacements, and those methods have led to further complication of the measuring procedure. Several methods of increasing the sensitivity of LIGA have now been proposed. One such method involves the introduction of an additional mirror into a two-arm interferometer. That mirror switches the light flux from one arm to the other in synchronism with the period of the gravitational wave and as a result the effective optical power increases [46].

Interferometric methods of GW radiation detection have been examined in detail by Kulagin [47], who calculated the signal/noise ratio for the Fabry–Perot interferometer for various cavity tuning modes.

Meers [48, 49] considered multibeam GW antenna systems with an additional semitransmitting mirror in front of the photodetector; he proposed a method of nonresonant recycling of the light energy and, for the first time, a double recycling system. The results of experimental studies of the latter system with a small cavity and a low optical coherent pumping power are given by Strain and Meers [50]. A seven-fold increase in the signal/noise ratio was recorded in the experiments, and agreement with calculations was obtained.

Morozov and others [51–55] developed a heterodyne method of gravitational radiation detection based on the Fabry–Perot cavity, a GW detection method using low-frequency optical resonance. They also developed a fairly complete mathematical model of the Fabry–Perot cavity in a GW field on the basis of the solution of a self-consistent system of differential equations describing the motion of the Fabry–Perot cavity mirrors and also carried out calculations on the optimization of the Fabry–Perot cavity parameters.

Krolak et al. [56] optimized a multiple-arm Fabry–Perot cavity for detecting gravitational waves from colliding binary stars. Considering a system with ordinary and double re-reflections in a Fabry–Perot cavity, they obtained expressions for the spectral density of noise and calculated the signal/noise ratio for different versions of antennas with a Fabry–Perot cavity. The problem of stabilization and the possible fabrication of fiber-optic interferometers were examined by Izmailov et al. [57]. The methods of increasing the sensitivity include the use of quantum unperturbed measurements, in which quantum state interferometry is carried out. Those methods were applied to both Weber GW antennas and to LIGA [58].

The above methods of GW detection reflected the action of the gravitational waves on one degree of freedom of the antenna: optical, acoustic, or torsional. Combined antennas are those in which the gravitational wave acts on two degrees of freedom. As a rule, those methods increase the reliability of signal discrimination against the noise background. An example is LIGA, in which the free masses are made in the form of Weber cylinders [59], thus allowing the results of interferometric and resonant detection systems to be compared and the influence of thermal noise to be decreased.

In GW antennas of another system, two Weber cylinders are complemented with a Fabry–Perot cavity, which reacts to a change in the separation between the cylinders [60]. The acoustic degree of freedom can also be used in LIGA when the test bodies are made of fused quartz [61].

Space GW antennas include antennas that detect the variation of the spacing between the test bodies at distances of the order of the dimensions of the solar system. The large dimensions of those antennas permit detection of low-frequency gravitational waves, which have a fairly large amplitude.

Also in the same class are antennas that detect signals by measurement of the time it takes an electromagnetic signal to propagate to a spacecraft, by Doppler tracking of the spacecraft, and a laser space interferometric GW antenna. One attempt at GW detection by measuring the time of propagation of the signal to the Voyager 1 probe over several days was reported by Helling [62]. A method of detecting gravitational radiation by the modulation of the Doppler frequency shift of an electromagnetic signal propagated between a ground-based tracking station and a probe was given by Bertotti [63]. Interferometric detection of low-frequency by means of a multiple-arm interferometer was considered by Anderson [64].

An orbital ring laser gyroscope, consisting of two earth satellites moving in circular orbits and exchanging light beams, was proposed by Chaboyer and Henriksen [65] for detection of pulsed gravitational waves.

The possibility of applying a radio interferometer with a baseline of the order of $1.5 \cdot 10^{11}$ m was explored by Braginsky et al. [66], who demonstrated that the resolution is five orders of magnitude higher when an optical interferometer is used.

The most detailed laser interferometer version of a space GW antenna was considered by Jafry et al. [67] The interferometer should have a V configuration and should incorporate four lasers on board four spacecraft in heliocentric orbits with a one-year period. The optical center of the interferometer is formed by two in-phase lasers 200 km apart. The other lasers are spaced $5 \cdot 10^{8}$ km apart.

Astronomical methods of gravitational radiation detection are divided into three groups: methods based on tracking of electromagnetic radiation that passes through a region of strong gravitational wave, methods based on tracking of astronomical objects that change their properties near the GW source, as well as methods based on the radiative properties of atoms in the presence of a GW. The first group includes methods based on the effect where the angle of direction to a star changes when a GW passes [68], the effect of the delay of the image of objects on a gravitational lens [69], the influence of a GW on the background of microwave electromagnetic radiation [70], and the effect of periodic variation of the position of a star as a result of the passage of electromagnetic radiation near a GW source [71]. The second group comprises methods constructed on the effect of the frequency shift of motion along the spiral of binary stars under the action of a GW [72], and the action of a GW on a rotating neutron star [73]. The third group contains methods based on the effect of the variation of the frequency of radiation of a hydrogen atom near a GW source [74], the probability of the passage of a Rydberg atom in a GW field [75], and intensification of stellar electromagnetic radiation, passing through a maser cloud with gravitational-wave-induced frequency shift of the passage of a re-radiating atom [76].

Conclusion. The methods for the detection of gravitational radiation discussed here have different degrees of theoretical and technical development. Some of them (e.g., astronomical methods) depend on the influence that the earth's atmosphere has on the transmission of electromagnetic radiation and require that the equipment be placed beyond the limits of the atmosphere. Some of the methods can be implemented in gravitational-wave antennas such as LIGO, VIGRO, LIZA, etc., that exist or are under construction.

On the whole, the LIGA project, which is in the construction stage and has sensitivity reserve, can be said to be the most promising, on the one hand, and is fairly well technically equipped, on the other hand. That type of wide-band gravitational-wave antennas has a mass of possibilities in regard to GW detection methods, signal discrimination methods, use of quantum nondestructive measurements, and connection into combined GW antennas and into an antenna network.

The classification given here determines the most general approaches to GW detection. Its further development can be directed along the path of giving a more detailed description of the method with consideration of the salient features of the measuring channel formation, signal discrimination methods, and choice of an optimal system to ensure sufficient sensitivity.

REFERENCES

1. A. Einstein, *Maherungsweise Integration der Fildgleichungen der Gravitation*, Academic Preuss. Akad. Wiss., Berlin (1916), p. 688.
2. J. H. Taylor and J. M. Weisberg, *Astrophys. J.*, **253**, No. 2, Pt. 1, 908 (1982).
3. J. H. Taylor, *Proc. 2 Marcel Gross Meeting on General Relativity*, Pt. A, 15 (1982).
4. J. Weber, *Topics in Theoretical and Experimental Gravitation Physics*, V. De Sabbata and J. Weber (eds.), Plenum Press, New York–London (1977).
5. E. Amaldi and G. Pizzella, *Nuovo Cim.*, **9**, 829 (1986).
6. V. B. Braginskii et al., *Zh. Eksp. Teor. Fiz.*, **66**, No. 3, 801 (1974).
7. P. Bonifazi and M. Visco, *Nuovo Cim.*, **15**, No. 6, 943 (1992).
8. M. Bassan, *Class. Quant. Grav.*, **11**, No. 6A, 39 (1994).
9. F. Bordoni and M. Karim, *ibid.*, p. 61.
10. E. Coccia et al., *Nucl. Instrum. Methods*, **355**, No. 2–3, 624 (1995).
11. H. Hirakawa, *Proc. 2 Marcel Gross Meeting on General Relativity,* Pt. A, 21 (1982).
12. Ico Ken-ichi et al., *J. Phys. Soc. Jpn.*, **54**, No. 5, 1697 (1985).
13. E. Coccia and J. A. Lobo, *Lab. Naz. Frascati (Rapp.)*, No. 95–010, 1 (1985).
14. E. K. Luchik and V. N. Rudenko, *Astron. Zh.*, **67**, 1074 (1990).
15. É. B. Gliner and I. G. Mitrofanov, *Zh. Eksp. Teor. Fiz.*, **76**, No. 6, 1873 (1979).
16. T. Suzuki, N. Akasaka, and K. Morimoto, *Rev. Sci. Instrum.*, **63**, No. 3, 1880 (1992).
17. V. B. Braginskii, V. P. Mitrofanov, and V. N. Yakimov, *Probl. Teor. Gravit. Element. Chast.*, No. 17, 6 (1986).
18. A. V. Gusev and V. N. Rudenko, *Statistical and Quantum Physics and Its Applications* [in Russian], Izd. Mosk. Gos. Univ., Moscow (1986).
19. V. B. Braginskii and M. B. Menskii, *Pis'ma Zh. Eksp. Teor. Fiz.*, **13**, 585 (1971).
20. A. Kulak, *Acta Phys. Pol.*, **B15**, No. 1, 3 (1984).
21. T. Mengxi and Li Fangyu, *Intern. Centre Theor. Phys. (Preprint)*, No. 42, 1 (1990).
22. Jeeva Amandan, *Phys. Lett.*, **A110**, No. 9, 446 (1995).
23. Peng Huei and Peng Bo, *Gen. Relat. Gravit.*, **22**, No. 1, 45 (1990).
24. R. V. Wagoner, C. M. Will, and H. J. Paik, *Phys. Rev.*, **D19**, No. 8, 2325 (1979).
25. B. Mours and M. Yvert, *Phys. Lett.*, **A220**, No. 9, 446 (1995).
26. J. Weber, *Nuovo Cim.*, **B109**, No. 8, 850 (1994).
27. R. R. Tamello, "Effect of gravitational radiation pressure and its amplification," *Preprint NF-38*, Otd. Fiz. Astron., Akad, Nauk ÉSSR, Tallin (1987).
28. M. V. Sazhin, *Vestn. MGU, Fiz. Astron.*, **23**, No. 4, 45 (1982).
29. G. Callagari, *Acta Phys. Hung.*, **70**, No. 1–2, 19 (1982).
30. M. V. Danileiko et al., *Pis'ma Zh. Eksp. Teor. Fiz.*, **39**, No. 9, 428 (1984).
31. E. Iacopini et al., *Phys. Lett.*, **A73**, No. 2, 140 (1979).
32. V. Khizhnyakov, *Izv. Akad, Nauk ÉSSR, Otd. Fiz. Mat.*, **37**, No. 2, 241 (1988).
33. B. V. Kulagin and V. N. Rudenko, *Phys. Lett.*, **A143**, No. 8, 353 (1980).
34. V. B. Braginskii and L. P. Grishchuk, *Zh. Eksp. Teor. Fiz.*, **89**, No. 3, 744 (1986).
35. V. B. Braginsky and Kip S. Torne, *Nature*, **327**, No. 6118, 123 (1987).
36. C. F. Teissier, *Ann. Phys. Fr.*, **10**, No. 3, 263 (1985).
37. P. G. Akishin et al., "Two-wave parametric method of gravitational-wave detection," *JINR Preprint No. 13–85–968*, Dubna (1985).
38. M. E. Gertsenshtein and V. I. Pustovoit, *Zh. Eksp. Teor. Fiz.*, **43**, 605 (1962).
39. R. W. P. Drever, *Gen. Relativ. Gravitat. Inv. Papers and Discussion. Rept. 10 Intern. Conf.*, Padua, July 3–8, 1983, p. 397 (1984).
40. K. S. Torne, *Res. Modern Phys.*, **52**, No. 2, Pt. 1, 285 (1980).
41. V. N. Rudenko, *Einstein Coillection* [in Russian], Nauka, Moscow (1990).
42. G. Pizzella, *Gravit. Wave Data Anal. Proc. Nato Adv. Res. Workshop, Cardiff, 1987*. p. 173 (1989).

43. V. B. Braginskii et al., *Zh. Eksp. Teor. Fiz.*, **66**, No. 3, 801 (1974).
44. V. N. Rudenko and M. V. Sazhin, *Kvant. Elektron*, (Leningrad), **7**, No. 11, 2344 (1980).
45. A. D. Alekseev et al., *Zh. Eksp. Teor. Fiz.*, **79**, No. 4, 1141 (1980).
46. J.-Y. Vinet, *J. Physique*, **47**, 639 (1986).
47. V. V. Kulagin, *Interferometer Methods of Measurement in a Gravitational-Wave Experiment*, Author's Abstract of Doctoral Dissertation [in Russian], Moscow (1987).
48. B. J. Meers, *Phys. Rev.*, **D38**, No. 8, 2317 (1988).
49. B. J. Meers, *Phys. Rev. Lett.*, **A142**, No. 8–9, 465 (1989).
50. K. A. Strain and B. J. Meers, *Phys. Rev. Lett.*, **66**, No. 11, 1391 (1991).
51. A. N. Morozov and V. O. Gladyshev, *Izmer. Tekh*., No. 10, 26 (1991).
52. V. O. Gladyshev and A. N. Morozov, *Pis'ma Zh. Tekh. Fiz.*, **17**, No. 19, 11 (1991).
53. V. O. Gladyshev and A. N. Morozov, *Pis'ma Zh. Tekh. Fiz.*, **19**, No. 14, 38 (1993).
54. V. O. Gladyshev and A. N. Morozov, *J. Moscow Phys. Soc.*, **6**, 1 (1996).
55. V. O. Gladyshev and A. N. Morozov, *Irreversible Processes in a Multiple-Beam Fabry–Perot Interferometer* [in Russian], Izd. EATK GA, Egor'evsk (1996).
56. A. Krolak, J. A. Lobo, and B. J. Meers, *Phys. Rev*., **D43**, No. 8, 2470 (1991).
57. G. N. Izmailov et al., *Zh. Tekh. Fiz.*, No. 6, 1194 (1987).
58. W. Meier, *Exp. Techn. Phys.*, **32**, No. 2, 109 (1984).
59. V. V. Kulagin, A. G. Polnarev, and V. N. Rudenko, *Zh. Eksp. Teor. Fiz.*, **91**, No. 5, 1553 (1987).
60. J. P. Richard, *Phys. Rev*., **D46**, No. 6, 2309 (1992).
61. V. B. Braginskii, V. P. Mitrofanov, and O. A. Okhrimenko, *Pis'ma Zh. Eksp. Teor. Fiz.*, **55**, No. 7–8, 424 (1992).
62. R. W. Helling, *Rayonn. Gravitational NATO ASI*, Centre phys. Des Houches, 485 (1983).
63. B. Bertotti, "Intern. Solar Polar Mission", *Sci. Invest*., Paris, 255 (1983).
64. A. J. Anderson, *Proc. Int. Assoc. Geod. Symp.*, Vancouver (1987), Vol. 1, p. 83.
65. Brian, Chaboyer, and R. Henriksen, *Phys. Lett*., **A132**, No. 8–9, 391 (1988).
66. V. B. Braginsky et al., *Intern. Centre Theor. Phys. (Preprint)*, No. 392, 1 (1994).
67. Y. R. Jafry, J. Cornelisse, and R. Reinhard, *ESA J.*, **18**, No. 3, 219 (1994).
68. R. Fakir, *Astrophys. J.*, **418**, No. 1, Pt. 1, 202 (1993).
69. B. Allen, *Phys. Rev. Lett*., **63**, No. 19, 2017 (1989).
70. E. V. Linder, *Astrophys. J.*, **326**, No. 2, Pt. 1, 517 (1988).
71. R. Fakir, *Astrophys. J.*, **426**, No. 1, Pt. 1, 74 (1994).
72. S. Smith, *Phys. Rev. D.*, **36**, No. 10, 2901 (1987).
73. V. I. Denisov, *Experimental Tests of the Theory of Gravitation. Theory* [in Russian], Atomizdat, Moscow (1989).
74. T. K. Leen, L. Parker, and K. O. Pimentel, *Gen Relat. and Gravit.*, **15**, No. 8, 761 (1983).
75. U. Fischer, *Class and Quantum Grav*., **11**, No. 2, 463 (1994).
76. S. V. Spivarov, *Phys. Rev*., **A55**, No. 5, 3704 (1997).