Current status of GW experiment and multi-messenger astronomy

V. N. Rudenko

Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskii prospect 13, Moscow 119991, Russia; e-mail: rvn@sai.msu.ru

Abstract. A limited review of the status of advanced gravitational wave interferometers is presented. In addition, a new opto-acoustical gravitational detector OGRAN in the deep underground of BNO INR RAS is described. The second part of the paper contains a short description of the "multi-messenger astronomy" approach in the context of the GW detection. Various scenarios of such strategy proposed by different authors are discussed. Special attention is paid to the "neutrino-gravity correlation" which looks more or less realistic in respect of supernova events in the Milky Way and near-by galaxies.

Keywords: GW Detection, Multistage Collapses, Neutrino-EM-Gravity Correlations

1. Introduction

It seems that a pursuit for the Gravitational Wave Astronomy is stepped in its decisive stage: three big wide frequency band gravitational antennae (free mass laser gravitational interferometers) finished the upgrade process and at present are going through the commissioning phase [1]. They will enter a new qualitative state when the expected rate of gravitational stochastic signals can reach the average number of events up to several ones per day [2]. A distance from which these antennae are capable to register a signal is estimated by the value of few hundred Mpc, i.e. it is the cosmological scale of distance. In this talk we very briefly present the essence of the last modernization of these instruments, describe an original national OGRAN antenna of moderate sensitivity as well and finally discuss the problem of multichannel reception in searching for gravitational wave signals, so called the strategy of "multi-messenger astronomy".

2. Sensitivity jump in advanced interferometers

In Fig.1 one can look at the noise level suppressing after transition from the old version of LIGO GW interferometers to new advanced instruments [3]. The jump of five times in the registered amplitude spectral component and more than one order of value in the signal power spectral density are demonstrated in this graph. It was achieved due to the following modernization of hardware in the three key nodes of the setup. First, the quality of seismic isolation was improved so that the noise spectral density $h = 10^{-21}\mathrm{Hz}^{-1/2}$, which was typical for the frequency region 50 Hz in the first setup version, was shifted now to the region of 10 Hz. Second, the same shift was realized for the mirror's Brownian noises with the typical spectral density $h = 10^{-22}\mathrm{Hz}^{-1/2}$. Third, the photon noise reduction was realized by increasing the pump power so that at the frequency ~1 kHz the amplitude spectral density was evaluated from $h = 10^{-22}\,\mathrm{Hz}^{-1/2}$ to the smallest level $h = 5\cdot10^{-23}\mathrm{Hz}^{-1/2}$.

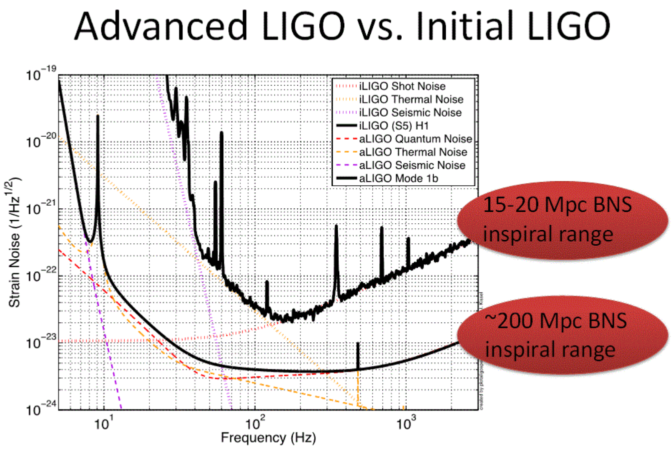


Fig1. *Comparison of the initial and advance LIGO noise spectral density.*

Approximately the same improvement was performed after modernization of the VIRGO setup [4] (see Fig.2). To illustrate capabilities of these instruments in solution of the problem of GW astrophysical signals detection we present Fig.3 containing the forecast of relativistic binary calescence event reliable registration from the distance 200 Mpc with the rate of events ~ 10 per day. [2, 3, 4]. Together with these extremely advanced setups the other ones – cryogenic resonance bar detectors, NAUTILUS and AURIGA, with the narrow reception frequency band in kilohertz region with sensitivity h = 10^{-21}Hz$^{-1/2}$, – were in operation during last few years [5, 6]. It is worth mentioning here that recently a new original resonance opto-acoustical bar detector OGRAN with a moderate sensitivity was installed in the deep underground of the Baksan Neutrino Observatory [7, 8].

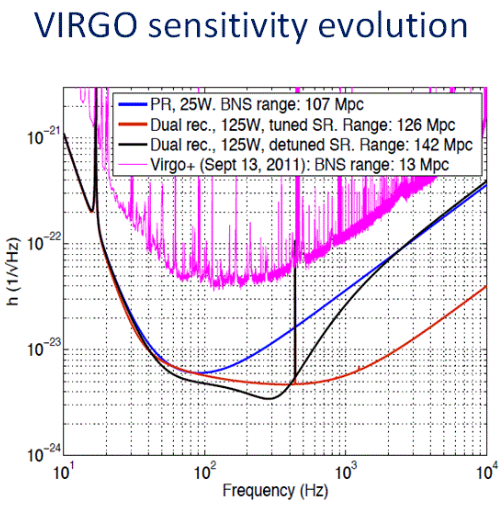
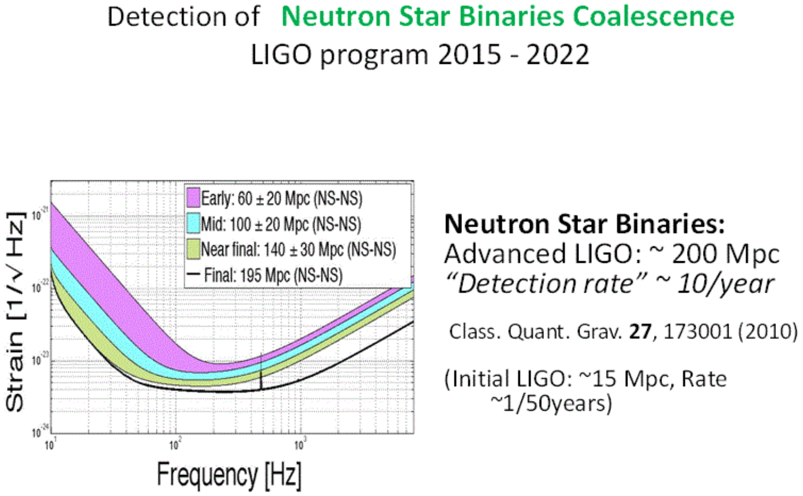


Fig2. *The same comparison for VIRGO interferometer.*



Detection of **Neutron Star Binaries Coalescence**
LIGO program 2015 - 2022

Neutron Star Binaries:
Advanced LIGO: ~ 200 Mpc
"Detection rate" ~ 10/year

Class. Quant. Grav. **27**, 173001 (2010)

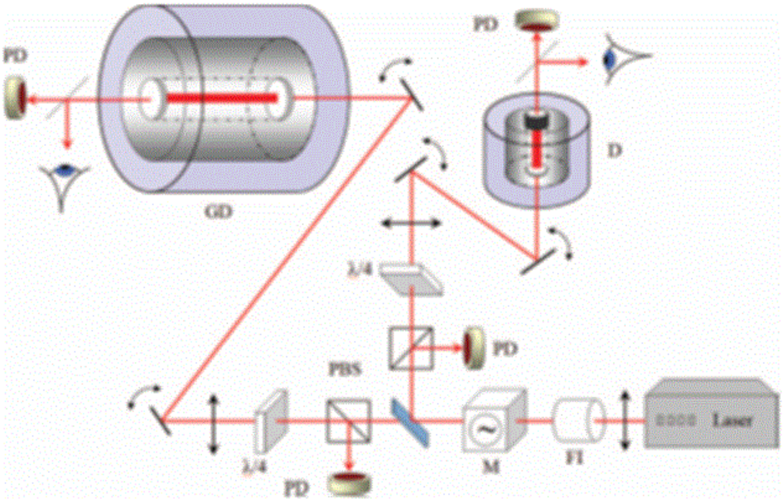
(Initial LIGO: ~15 Mpc, Rate
~1/50years)

Fig3. *Expected efficiency of reception of the GW- signal from Neutron Star Binaries coalescence for advance LIGO*

3. The opto–acoustical detector in BNO INR RAS

The idea of construction of a GW detector as an acoustical resonance bar coupled with the optical FP cavity composed by mirrors attached to the bar ends was considered in [9] and [10]. A new quality was emphasized of such a combination: (a) a more complex structure of signal response, containing separately acoustical and optical parts, and (b) a possibility to get sensitivity at the level of bar Brownian noise in a relatively wide spectral frequency range due to the small back action of optical read out. The plan for implementation of this idea was reported as the OGRAN project and the first pilot model was presented in [11]. At present the full scale setup was constructed, tested and installed into underground facilities of BNO INR RAS. A perspective of the next development is associated with a cryogenic version of the opto-acoustical bar considered in [12] having a final goal sensitivity $h{\sim}10^{-23}$ $Hz^{-1/2}$.

The principal opto-electronic scheme of the setup is given in Fig. 4. Generally, it belongs to the design type called a comparator of optical standards. It is composed of two feedback loops. The first one couples the FP cavity at the large bar (OGRAN detector) with the pump laser coercing a generated frequency to be in optical resonance with bar cavity. Thus any change of the FP optical length is converted into the pump beam frequency variation. The second loop is the measuring one. It consists of the additional FP reference cavity or a “frequency discriminator” illuminated by the same pump laser but tuned in resonance by an independent piezo-ceramic driver attached to the one of discriminator’s mirror. So its output signal is proportional to the frequency difference of the pump and discriminator cavity. It means that any perturbation of the detector bar cavity is reflected in the discriminator signal. A similar scheme was tested for the AURIGA optical bar detector [13]. However, the OGRAN detector has a big FP cavity at the same scale as its acoustical resonance bar. Meanwhile the AURIGA project used a mini gap FP resonator (a kind of optical accelerometer) placed on a displacement transducer attached to one of the bar detector ends. Just this feature presents the OGRAN physical specificity: the gravitational wave interacts not only with acoustical degree of freedom (the resonance bar) but with the EM field in the cavity as well (that is why one can tell about a complex structure of signal response with optical and acoustical parts. A payment for this originality is the technical problem of constructing a large scale high finesse FP cavity rigidly coupled with the acoustical resonator without loosing its high mechanical resonance quality factor Q.



The principal opto-electronic scheme of the setup OGRAN. GD - gravitational detector, PD - photo detector, D - discriminator, FI - Faraday isolator, M - modulator, and PBS - polarized beam splitter.

Fig4 *Optical scheme of the OGRAN*

The potential sensitivity of such a gravity gradiometer is defined by the thermal Brownian noise of fundamental acoustical mode. Under optimal filtration procedure, the minimum registered perturbation of the OGRAN optical length in the bandwidth Δf is read as $h \sim 10^{-20} (F\Delta f)^{1/2} Hz^{-1/2}$. Here the numerical factor corresponds to the OGRAN parameters: $M = 10^3$ kg, $L = 2$m, $\omega_0/2\pi = 1.3$ kHz, and $T = 300$ K, $Q = 10^5$. The noise factor F describes the excess of optical readout fluctuation over the thermal noise level. So for the room temperature OGRAN detector, the integral potential sensitivity $h \sim 10^{-19}$ might be provided in the bandwidth _f = 100 Hz if $F \sim 1$. Thus, the main technical challenge for the OGRAN construction was to provide optical readout with the noise factor F = 1.

Calculation of the noise factor for the optical readout associated with the Pound-Drever technique resulted in the formula $F = (2M/\tau)\,(G_e/G_T)^{1/2}$, where the following notations were used: a spectral density of optical fluctuations $G_e = B\omega_0^2(2h\nu_e/\eta P)(\lambda_e/2\pi N)^2$ with the parameters: $\eta \sim 0.7$ – the photodiode quantum efficiency, N – the number of reflection of FP cavity (proportional to finesse), $\tau = (1/\Delta f)$ – the time of measurement, B = (1 - 1000) – the phenomenological factor of exceeding the Piossonian level of laser noise; the spectral density of the bar thermal (Brownian) fluctuations $G_T = 2kTM\omega_0/Q$; the parameter M is the effective mass was roughly equal to the half of total bar mass; τ is the measurement time (the resonance signal duration for the optimal filtration) or the inverse value of filtering bandwidth Δf. Under the maximum laser power P = 2W, the incoming luminosity for each of both FP resonators cannot exceed a half of watt. But due to losses in the light guide elements and the interference contrast ~ 10% the real value of effective power is P = 0.01W. Substituting all numerical data together with the measurement time $\tau = 0.01$ s leads to the resulting estimate of the required number of reflections (mirror's quality): $N = (10^3–10^4)$ (or better). Thus the uncooled opto-acoustical gravitational antenna was constructed for a multi-channel mode operation in the deep underground of Baksan Neutrino Observatory (look at the photo Fig.5 in parallel with Baksan Underground Scintillator Telescope (BUST) involved in the collapse searching for the program.

In the last part of this article we present also a brief prospect of the multi-channel observational strategy.

Fig5. *The OGRAN detector chamber in the dust-protected box.*

4. Strategy of the multi–messenger astronomy

The task of direct detection of gravitational radiation from relativistic extra terrestrial sources is very difficult due to extremely weak influence of gravitational waves (GW) on detectors and due to unpredictable nature of relativistic catastrophic events in the Universe. Up to now no reliable GW signal has been registered by available GW facilities of both types: resonance bar detectors and free-mass laser interferometers. In such a situation the idea of multichannel registration was proposed to increase the detection probability. Still, cooperative observations using different methods can, on the one hand, help to make the claims about GW detection more robust, i.e. to raise the confidence of GW detection, on the other hand, can significantly deepen our understanding of the physics related to astrophysical sources of GWs (see a brief summary in [14]).

Observations aimed at GW detection can be divided into two broad types: multi-wavelength electromagnetic (EM) and non-EM ones. The latter are mostly related to neutrino (ν)-signals. For EM observations we can also speak about two types: the follow-up observations (when registration of a GW signal serves as a trigger) and the independent observations when, for example, coincidence of two transients is derived from an off-line reduction. Below we will briefly comment on each approach, with more detailed discussion of planned observations with the OGRAN detector.

Two main sources for transient GW signals with possible counterparts are supernovae (SNe) and binary coalescence where neutron stars (NS) are involved.

There is a plethora of data related to observations of (SNe) including ν-signals [15, 16]

Unfortunately, the present-day detectors are sensitive to GW signal from an SN explosion only in a very limited volume which includes the Milky Way and close-by galaxies. The rate of core-collapse SNe in our Galaxy is ~ 1/30 yrs^{-1}. This is not very promising. In addition, in some cases we can miss the optical counterpart due to huge interstellar absorption [17]. In this case only simultaneous detection of a -burst can confirm the detection. The most optimistic scenario – two-stage collapse – was proposed and developed to explain double neutrino signal from the SN1987A.[18 – 20]

Baksan Neutrino Observatory of the Institute for Nuclear Research, Russian Academy of Science (BNO INR RAS) has two instruments for the multi-messenger GW astronomy. The first one is the Baksan Underground Scintillation Telescope (BUST) which operates in a special mode: “searching for neutrino bursts from core collapse supernovae” [21, 22]. The second one is the setup OGRAN – an opto-acoustical gravitational wave antenna which is now in the assembling stage at the underground BNO site. [23]. Both detectors have moderate sensitivity sufficient for registration of core collapse events in the Galaxy and close environment ~100 kpc, i.e. their applications are limited by “searching for rare events”. The BUST resolution is determined by the neutrino (antineutrino) threshold energy (8 – 10) MeV registered during the time 20 sec through the secondary electrons (positrons). The OGRAN sensitivity corresponds to the threshold of spectral metric perturbations at the level 10^{-19} -10^{-18} Hz$^{-1/2}$ in the bandwidth 1-10 Hz around the central frequency 1.3 kHz [23].

Despite moderate sensitivity, a reasonable program of two-channel (ν and GWs) search for transient signals can be proposed for these instruments. Moreover, such program was stimulated by the well-known precedent of proposed ν-GW correlation for the SN1987A event [24 – 27]. Although, later analysis of the SN1987A data did not confirm the fact of ν-GW correlation [28, 29] it has given a push for a non-standard two-stage scenario of stellar collapse (see a review in [17]). The mean neutrino energy (during the first stage) in this model is 30–40 MeV. Another mode l [30] takes into account a large-scale convection caused by non-equilibrium neutronization of matter in the central region of a proto-NS. The large-scale convection provides a high yield of high energy neutrinos from the central region of a presupernova. The average energy of neutrinos is 30–50 MeV which is larger than in the case of diffusion. A drawback of these models is related to absence of correspondent estimates for GW radiation. In fact, there is a deficit of realistic theoretical models of astrophysical sources which admit simultaneous calculation of the neutrino and gravitational radiation bursts. For this reason a strategy of data analysis in multichannel detection of relativistic catastrophic events might be based more on empirical intuition than on a relable theoretical scenario. The first example of such strategy was given in the data processing of SN1987A phenomenon. The key point is the supposition that registration of neutrino (or an EM counterpart) event provides tic marks for the gravitational channel, i.e. GW signal is searched in the vicinity of this moment (Fig.6). Such approach to the data analysis enormously reduces the volume of stochastic data from the GW channel which has to be processed, and so we have an increase of the detection probability. The more important characteristic is the expected time delay $\Delta\tau k$ between the registered arrival time of a neutrino burst (an astrophysical event) τk and the moment of the GW burst appearance tk so that: $\tau k = tk+\Delta k$. It would be desirable to have a prior estimate of the time delay from theoretical understanding of internal dynamics of radiative processes in the source. If such knowledge is absent one has to accept a hypothesis of a prior homogeneous distribution for time delay inside a resonably wide interval around tk. In the simplest model of identical nature of mutliradiation sources the time delay is taken the same for all registered neutrino (or EM) events. As the “observable variable” (or “sufficient statistics”) it is natural to choose a variable proportional to the empirical correlation function between the row of registered neutrino (or EM) events and gravitational detector noise data accounting for the supposed time delay shift. Composing the likelyhood ratio for this variable one can estimate the empirical value of the time shift through the standard procedure of likelyhood ratio maximization. Using this shift estimate one calculates the value of “observable variable” for comparison with the statistical threshold. The last one is calculated on the basis of an empirical record of a GW detector noise at intervals far from the moments of registered astrophysical events (neutrino or EM bursts).

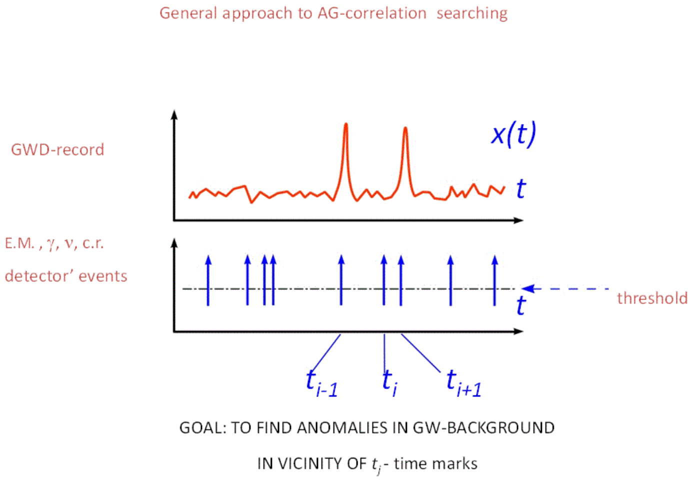


Fig6. *Illustration of the strategy a search for ν-gw coincident bursts.*

For LIGO/Virgo (as well as for ALIGO/adVirgo) the main sources are coalescing binaries (see a recent review in [32]). Black hole – black hole (BH) coalescence hardly can produce any (ν or EM) counterpart. But those events involving NSs are promising candidates. Many possibilities to produce a simultaneous EM burst or an afterglow have been discussed in the literature (see [33] and references therein).

Also the usage of new astronomical instruments (OpTIIX, ISS-Lobster) aboard the International Space Station (ISS) is planed to follow-up GW bursts [34], and the new wide-field X-ray instrument – NICER – is approved for installation on ISS.

One obvious task is to detect simultaneously a short GRB (SGRB) and a GW signal. The horizon for ALIGO/adVirgo is ~300 Mpc. SGRB are rare in such small volume, but if detected they are bright, and so their detection can be used as a tic mark to search for a GW burst in the data. Joint observations in X-rays and GWs can help to learn much more about the central engine and to determine parameters of the coalescing binary with better precision. However, less than 10% of GW bursts are expected to be accompanied by SGRB [33], and so the rate will be one in several years.

Better prospects exist for detection of an afterglow. Several mechanisms are duscussed, but one of the most promising is related to the so-called “kilonova” (see recent estimates and discussion in [35] and [36] for an early proposal). In this scenario the isotropic optical emission can be generated due to radioactive decay in an ejected envelope. Emission has unique spectral characteristics, so potentially it is not very difficult to identify such a source when it is discovered. Relatively quick follow-up by wide-field instruments can provide a discovery of an optical transient. Then the source potentially can be studied in dedicated observation in optics, X-rays and other wavebands.

Problems with using a GW burst as a trigger for follow-up observations are related to poor localization of GW-sources in the sky [32]. Even three working detectors (ALIGO/andVirgo) provide multiple vast “zones” which cannot be covered on a time scale of few days with large instruments.

While the paper has been prepared to publication, information appeared about the first registration of GW from merging black holes in a binary system. See Phys. Rev. Let. 116, 061102 (2016).

References

[1] R.X. Adhikari, Gravitational radiation detection with laser interferometry. Rev. Mod. Phys. vol.86, № 1, 2014

[2] M. A. Bizouard and M. A. Papa, Searching for gravitational waves with the LIGO and Virgo interfereometers. arXiv: 1304.4984 v1 17 Apr 2013

[3] The LIGO Scientific Collaboration. Advanced LIGO. Class.& Quantum Gravity. vol,32 (7); 074001, 2015.

[4] T. Accadia, F. Acernese, F. Antonucci et.al. Class.& Quantum Gravity. vol,32 ,020041, 2015

[5] P. Astone, D. Babusci, L. Baggio et al., Phys. Rev. D 76, 102001, (2007).

[6] M. De Rosa, L. Baggio, M. Cerdonio et al., Class.& Quantum Gravity vol. 19, 1919 (2002).

[7] S.N. Bagaev, L.B. Bezrukov, N.L. Kvashnin, V.A. Krysanov, S.I. Oreshkin, A.M. Motylev, S.M. Popov, V.N. Rudenko, A.A. Samoilenko, M.N. Skvortsov, I.S. Yudin, A high frequency resonance gravity gradiometer. Review of Scientific Instruments, vol. 85, № 065114, c.114-1-114-8.

[8] S.N. Bagaev, L.B. Bezrukov, N.L. Kvashnin, V.A. Krysanov, S.I. Oreshkin, A.M. Motylev, S.M. Popov, V.N. Rudenko, A.A. Samoilenko, M.N. Skvortsov, I.S. Yudin, Setup OGRAN as a high frequency resonance gravity gradiometer». arXiv: 1403.0827v1 [physics.ins det] 4 Mar 2014

[9] A.V. Gusev, V.V. Kulagin, and V.N. Rudenko, Room-temperature gravitational bar-detector with cryogenic level of sensitivity. Gravitation Cosmol. 2(1), 68–70 (1996)

[10] L. Bezrukov, S. Popov, V. Rudenko, A. Serdobolskii, and M. Skvortsov, Gravitational wave experiments and Baksan project OGRAN, in Astrophysics and Cosmology after Gamov: Theory and Observations, edited by G.S. Bisnovaty-Kogan et al. (Cambridge Scientific Publishers, 2007), pp. 125–138; e-print arXiv:gr-qc/0411083v1

[11] L.B. Bezrukov, N.L. Kvashnin, A.M. Motylev, S.I. Oreshkin, S.M. Popov, V.N. Rudenko, A.A. Samoilenko, and I.S. Yudin, Instrum. Exp. Tech. 53(3), 423–429 (2010).

[12] A.V. Gusev, V.N. Rudenko, S.A. Cheprasov, and M. Bassan, Classical Quantum Gravity 25(5), 055006 (2008).

[13] M. De Rosa, L. Baggio, M. Cerdonio et al., Classical Quantum Gravity 19, 1919 (2002).

[14] J.S. Bloom et al., ArXiv e-prints: 0902.1527 (February 2009).

[15] S.J. Smartt, ARA&A 47, 63(September 2009).

[16] K. Scholberg, Annual Review of Nuclear and Particle Science 62, 81(November 2012).

[17] C.W. Stubbs, Classical and Quantum Gravity 25, p. 184033(September 2008).

[18] V.S. Berezinskii, C. Castagnoli, V. I. Dokuchaev and P. Galeotti, Nuovo Cimento C Geophysics Space Physics C 11, 287(June 1988).

[19] V.S. Imshennik, Soviet Astronomy Letters 18, p. 194(June 1992).

[20] V.S. Imshennik and D. K. Nadyozhin, Soviet Astronomy Letters 18, p. 79 (March 1992).

[21] R.V. Novoseltseva et al., Bulletin of the Russian Academy of Science, Phys. 75, 419 (March 2011).

[22] R.V. Novoseltseva et al., ArXiv e-prints: 0910.0738 (Octtober 2009).

[23] L.B. Bezrukov et al., Instruments and Experimental Techniques 53, 423 (2010).

[24] M. Aglietta et al., EPL (Europhysics Letters) 3, 1315 (1987).

[25] E.N. Alekseev, L.N. Alekseeva, V.I. Volchenko and I.V. Krivosheina, Soviet Journal of Experimental and Theoretical Physics Letters 45, p. 589(May 1987).

[26] M. Aglietta, G. Badino, G. Bologna, C. Castagnoli and A. Castellina, Nuovo Cimento C Geophysics Space

Physics C 12, 75(February 1989).

[27] E.N. Alexeyev, Soviet Journal of Experimental and Theoretical Physics 110, 220 (February 2010).

[28] C.A. Dickson and B.F. Schutz, Phys. Rev. D 51, 2644(March 1995).

[29] V.N. Rudenko, A.V. Gusev, V.K. Kravchuk and M.P. Vinogradov, Soviet Journal of Experimental and Theoretical Physics 91, 845(November 2000).

[30] V.S. Imshennik and O.G. Ryazhskaya, Astronomy Letters 30, 14(January 2004).

[31] I.V. Baikov, V.M. Suslin, V.M. Chechetkin, V. Bychkov and L. Stenflo, AstronomyReports 51, 274(April 2007).

[32] N. Andersson et al., ArXiv e-prints: 1305.0816 (May 2013).

[33] B.D. Metzger and E. Berger, ApJ 746, p. 48(February 2012).

[34] J. Camp et al., ArXiv e-prints: 1304.3705 (April 2013).

[35] B.D. Metzger et al, MNRAS 406, 2650(August 2010).

[36] S. Rosswog, ApJ 634, 1202(December 2005).