Experiments with probe masses

V. B. Braginsky†

Department of Physics, Moscow State University, Moscow 119992, Russia

This contribution is part of the special series of Inaugural Articles by members of the National Academy of Sciences elected on April 25, 2006.

Contributed by V. B. Braginsky, November 29, 2006 (sent for review October 30, 2006)

It is reasonable to regard the experiments performed by C. Coulomb and H. Cavendish in the end of the 18th century as the beginning of laboratory experimental physics. These outstanding scientists have measured forces (accelerations) produced by electric charges and by gravitational "charges" on probe masses that were attached to torque balance. Among the variety of different research programs and projects existing today, experiments with probe masses are still playing an important role. In this short review, the achieved and planned sensitivities of very challenging LIGO (Laser Interferometer Gravitational wave Observatory) and LISA (Laser Interferometer Space Antennae) projects are described, and a list of nonsolved problems is discussed as well. The role of quantum fluctuations in high precision measurements is also outlined. Apart from these main topics, the limitations of sensitivity caused by cosmic rays and the prospects of clock frequency stability are presented.

gravitational waves | measurement

I. Classical and Quantum Limitations of Sensitivity in the Experiments with Probe Masses

In the simplest classical "case," when a probe mass (PM) m_p is coupled with a heat-bath by means of friction H, the Fluctuation–Dissipation Theorem (FDT) gives the limit for detectable value of AC acceleration

$$(\alpha_{PM})_{FDT} \simeq \frac{\sqrt{4k_B T H \Delta f}}{m_p}, \qquad [1]$$

where T is the heat-bath temperature, k_B is the Boltzmann constant, and Δf is the bandwidth of force acting on the PM $F = m_p \cdot a_{PM}$. Equation **1** is valid when the parameter H does not depend on frequency and if the time interval (averaging time) is equal to $\tau \simeq (\Delta f)^{-1}$.

If PM is in the absolute vacuum (no mechanical contact with the entourage-envelope), then the remaining fluctuating force acting on PM is the AC component of thermal radiation pressure F_{THERM} from the entourage if $T > 0$. This effect is a classical one (i.e., it exists due to fluctuations of envelope temperature in thermal equilibrium). This small effect will be discussed in *Section III*.

Simple calculations [almost 40 years old (1)] give another limit for the detectable force $F = m_p \cdot a_{PM}$, which acts on PM. This limit is of quantum origin; it depends on the chosen observable of the measuring device (meter). If PM is a part of the mechanical oscillator whose eigenfrequency is ω_m, and if $F = F_0 \sin\omega_m t$ during time interval τ, then using an optical Fabry–Perot resonator pumped by a laser as a continuous monitor of the coordinate, it is possible to measure the amplitude (1)

$$(F_0)_{SQL} \simeq \frac{2}{\tau}\sqrt{\hbar\,\omega_m m_p}. \qquad [2]$$

The term "Standard Quantum Limit" (SQL) was coined by K. S. Thorne. This limit can be obtained only provided that laser pumping power in the meter is equal to the optimal value:

$$W_{optim} = \frac{m_p \omega_m (1-R)^2 c^2}{\pi \tau \omega_{optic}}, \qquad [3]$$

where R is the mirrors reflectivity, c is the speed of light, and ω_{optic} is the laser frequency. If W is smaller or higher than W_{optim}, then the variance of output signal will give uncertainty $F_0 > (F_0)_{SQL}$. The origin of this limit is the back action of photon shot noise on m_p.

The analysis expanded to other mechanical objects (i.e., free mass, mechanical modes in the mass itself) and electromagnetic (e.m.) oscillators (e.m. modes in resonator) has shown that SQL also exists when continuous coordinate meters are used. Thus, there is a "family" of SQLs for different test objects.

To obtain sensitivity at the SQL level, it is necessary to decrease the values of $(a_{PM})_{FDT}$ by means of T and H decrease to reach the levels of

$$\frac{2k_B T \tau^2}{\tau^*} \leq \hbar \ \text{ for free mass}$$

and [4]

$$\frac{2k_B T \tau}{Q_m} \leq \hbar \ \text{ for mechanical oscillator.}$$

In Equation **4**, relaxation time $\tau^* = m_p \cdot H^{-1}$ and quality factor $Q_m = 2m_p \cdot \omega_m \cdot H^{-1}$.

After the formulation of Equations **1** and **2**, and Conditions **4**, several researchers have solved the problem how to circumvent the SQL. The "recipe" turns out to be simple: it is necessary to use meters that register not the coordinate but other observables. These types of measurements are called Quantum Non-Demolition (QND) (2–5). This class of measurements has attracted attention of experimentalists from the quantum optics community: in the end of the previous century, QND measurements were demonstrated in optical resonators (see review in ref. 6), and even the count of microwave photons without absorption has been realized and demonstrated (7).

QND-type measurements with PM have not been realized yet. But it is likely that in the not-too-distant future this type of experiments will be performed in the Laser Interferometer Gravitational wave Observatory (LIGO) project (see details in *Section II*) or elsewhere.

Concluding the introduction of this short review, it is appropriate to note that there exists another source of mechanical action on the object (free probe mass) that also has a pure quantum origin. This effect (at zero temperature) is due to the fluctuations of e.m. vacuum zero-point oscillations. It was pre-

Author contributions: V.B.B. wrote the paper.

The author declares no conflict of interest.

Abbreviations: e.m., electromagnetic; GW, gravitational wave; IJT, ion jet thruster; LIGO, Laser Interferometer Gravitational wave Observatory; LISA, Laser Interferometer Space Antennae; PM, probe mass; QND, Quantum Non-Demolition; RM, ruling mass; SQL, Standard Quantum Limit; Caltech, California Institute of Technology; MIT, Massachusetts Institute of Technology.

†E-mail: brag@hbar.phys.msu.ru.

dicted by G. Barton (8). This effect is very small, and it is necessary to fulfill relatively tough resonance conditions before it might become possible to demonstrate it (9).

II. LIGO Project: Achievements and Prospects

LIGO is a project aimed to detect gravitational waves (GWs) from astrophysical sources (e.g., supernova explosion, neutron stars merging) using terrestrial GW antennae [this concept was formulated by J. Weber in the mid-20th century (10)]. A GW is a wave of gradient of acceleration that is orthogonal to the vector of propagation. GW has the same speed of propagation as e.m. wave. Using two or more PMs separated by distance L, an observer can detect GWs using different meters. In the first stage [Initial LIGO (11–16)] and second stage (Advanced LIGO), the PMs are heavy mirrors: two pairs of mirrors in one antenna and two pairs in the second one. Each pair is a Fabry–Perot optical resonator; two pairs are orthogonal to each other, and the distance between PMs is $L = 4{\cdot}10^5$ cm. PMs (mirrors) are "gently" suspended in high vacuum. Thus, each antenna is a Michelson optical interferometer with two Fabry–Perot resonators in arms. A burst of gravitational radiation with frequency ω_{GW} creates an AC force, which is "applied" to one of the PMs with respect to another one. This force has an amplitude

$$F_{\mathrm{GW}} = \frac{1}{2}\, hLm_p\omega_{\mathrm{GW}}^2, \qquad [5]$$

which creates an amplitude of displacement ΔL of one free PM with respect to the second one

$$\Delta L = \frac{1}{2}\, hL, \qquad [6]$$

where h is the amplitude of metric perturbation (sometimes the term "strain" is used instead). At present (the end of 2006), the achieved sensitivity in Initial LIGO is close to $h \simeq 10^{-21}$ at $\omega_{\mathrm{GW}} = 2\pi{\cdot}10^2\ \mathrm{sec}^{-1}$ and bandwidth $\Delta\omega_{\mathrm{GW}} \simeq \omega_{\mathrm{GW}}$. The value of $h \simeq 10^{-21}$ corresponds to the displacement amplitude of one mirror with respect to another one $\Delta L \simeq 2{\cdot}10^{-16}$ cm. At frequencies higher and lower than $\omega_{\mathrm{GW}} \simeq 2\pi{\cdot}10^2\ \mathrm{sec}^{-1}$, the sensitivity of antenna is worse. The "total" antenna bandwidth spreads from $\omega_{\mathrm{GW}} \simeq 2\pi{\cdot}30\ \mathrm{sec}^{-1}$ up to $\omega_{\mathrm{GW}} \simeq 2\pi{\cdot}10^3\ \mathrm{sec}^{-1}$. It is worthwhile to note that during the 15 years that passed since 1981 [when the LIGO project was founded by K. S. Thorne, R. Drever from the California Institute of Technology (Caltech; Pasadena, CA), and R. Weiss from the Massachusetts Institute of Technology (MIT; Cambridge, MA), the group of devoted experimentalists has been working hard to realize the sensitivity of $\Delta L \simeq 2{\cdot}10^{-16}$ cm in a relatively small prototype of the antenna ($L \simeq 40$ m). This sensitivity was obtained in 1996 (17) when the full-scale Initial LIGO implementation began. It has taken several years to reach the planned sensitivity in full-scale Initial LIGO. At present, when the accumulation of data are on, the achieved sensitivity is sufficient to register a burst of GWs from a merging of two neutron stars at a distance of 14 megaparsecs away from our solar system.

Initially, LIGO was a project run by two teams from Caltech and MIT. Gradually, this national project has become an international one: several teams from Australia, the United Kingdom, Germany, Italy, France, Russia, and Japan joined it and created the LIGO Scientific Collaboration (LSC), where Caltech and MIT are playing the leading role. It is necessary to acknowledge the very important support of this work on LIGO by the National Science Foundation.

Simultaneously with the tuning and adjusting stages of Initial LIGO, the LSC has created the key elements of the second stage, called Advanced LIGO, with planned sensitivity of $h \simeq 10^{-22}$, which is close to the SQL (this limit exists because the readout meter in this stages is a coordinate meter). In Advanced LIGO, several important modifications of antennae parameters have been already made. These modifications are based on in-depth analysis of different kinds of noises not taken into account in Initial LIGO. In particular, to diminish thermoelastic noise [small ripples on the mirror surface predicted by M. Gorodetsky and S. Vyatchanin (18)] the size of the light spot on the mirror surface has been substantially increased. The steel wires on which mirrors are suspended will be replaced now by thin fibers made of very pure fused silica. V. Mitrofanov and K. Tokmakov (19) demonstrated that such fibers provide relaxation time $\tau^* \simeq$ 5.4 years $\simeq 1.5{\cdot}10^8$ sec. This value will "permit" the satisfaction of Condition **4** at room temperature for the averaging time $\tau \simeq 10^{-3}$ sec. Thus, the expected sensitivity in Advanced LIGO will be close to the SQL. Advanced LIGO will start to operate within 7 years, and the community of physicists may expect to obtain qualitatively new information, in particular: (*i*) the estimate of the population of neutron stars in the Metagalaxy and, consequently, the contribution of these stars to dark matter; (*ii*) the shape of gravitational burst from neutron stars may indicate which equation of state (from the existing list) would hold for neutron star matter; (*iii*) the analysis of signal shape from black holes merging may permit the general relativity testing in the ultrarelativistic case (where the relative difference between the gravitational potential and c^2 is much less than unity); and (*iv*) a test of the prediction made by V. Imshennik and I. Popov (20) that supernova birth is a nonsymmetric event.

At present, many groups from LSC have started to propose and analyze the new versions of LIGO readout meters, which might be used after the Advanced LIGO is commissioned. These meters are designed to circumvent the SQL, i.e., to exclude the usage of continuous monitoring of the coordinate (see, e.g., refs. 21 and 22). On the one hand, these efforts are promising, and, on the other hand, they are not completely elaborated to be ready for direct tests. It is worthwhile to note here that if a speed meter is used instead of coordinate meter to record the relative motion of the mirrors, then in this experiment it will be possible to prove that with this test it is possible to measure the PM kinetic energy with the error $\Delta\mathcal{E}$ smaller than $\hbar/(2\tau)$ and thus to prove experimentally that in the famous dispute between A. Einstein and N. Bohr, Einstein was not wrong (see also ref. 23).

Summing up this section, it is possible to conclude that to "enter" the "zone" of resolution better than SQL, the members of LSC have to realize very small frictions H in many degrees of freedom of PM and its suspension. For example, to reach the level of $h \simeq 0.3h_{\mathrm{SQL}}$ with averaging time $\tau \simeq 5{\cdot}10^{-3}$ sec (i.e., $\omega_{\mathrm{grav}} \simeq 2\pi{\cdot}10^2\ \mathrm{sec}^{-1}$), it is necessary to have the suspension relaxation time $\tau^* \simeq 2{\cdot}10^{10}$ sec $\simeq$ 600 years.

III. The Status of LISA Project

Over more than a decade, several groups of scientists have been developing and testing different parts of Laser Interferometer Space Antennae (LISA). Initially, the LISA project's main concept was to operate with three drag-free satellites separated from one another by the distance of $L = 5{\cdot}10^6$ km $= 5{\cdot}10^{11}$ cm. These satellites have to "work" as Michelson interferometer to register low-frequency GWs (from $\omega_{\mathrm{GW}} = 2\pi{\cdot}10^{-5}\ \mathrm{sec}^{-1}$ up to $\omega_{\mathrm{GW}} = 2\pi{\cdot}10^{-1}\ \mathrm{sec}^{-1}$) (see, e.g., refs. 24 and 25). The highest planned sensitivity of this GW antenna has to be at the level of $h \simeq 10^{-21}$ near the frequency $\omega_{\mathrm{GW}} \simeq 3{\cdot}10^{-3}\ \mathrm{sec}^{-1}$. Near this frequency, the amplitude of relative displacement of one satellite with respect to another should be $\Delta L = \frac{1}{2}hL \simeq 2.5{\cdot}10^{-10}$ cm. This value corresponds to the amplitude of acceleration $(A_{\mathrm{GW}})_{\mathrm{AC}} \simeq 2{\cdot}10^{-15}\ \mathrm{cm/sec}^2$. The analysis and tests performed already by several groups being very important and fruitful, nevertheless, have not solved all of the problems to guarantee that the goals of the LISA mission will be achieved. Several important and not yet solved problems are listed below.

a. Noises from Ion Jet Thrusters (IJTs). Three LISA satellites have to "fly" along the Earth orbit. The solar light pressure force F_{solar} produces a DC acceleration

$$(A_{solar})_{DC} \simeq \frac{W_{solar}}{cM_{\Sigma}} \simeq 3{\cdot}10^{-6}\text{cm/sec}^2, \qquad [7]$$

where $W_{solar} \simeq 1$ kW $= 10^{10}$ erg/sec, if the satellite geometrical cross section is equal to 10^4 cm^2, c is the speed of light, and $M_{\Sigma} = 10^5$ g is the total satellite mass. Random variations of W_{solar} will be a source of AC component of its acceleration. Both $(A_{solar})_{DC}$ and $(A_{solar})_{AC}$ have to be compensated by IJTs that will be guided by signals from the ruling mass (RM) situated in the middle of the satellite. It is appropriate to note that the first drag-free satellite made by D. DeBra and colleagues (41) from Stanford University (Stanford, CA) reached the level of compensation of 10^{-8} cm/sec^2. In LISA, the compensation has to be almost seven orders better.

Assuming that IJT will "spend" the total mass of $m_{\Sigma} = 1$ g per year and that ion mass is $m_{ion} = 10^{-22}$ g, ion speed is $v = 10^7$ cm/sec (this corresponds to the accelerating voltage of 3 kV), then during the time interval of $\tau = 10^3$ sec, the total number of "used" ions will be $N_{\tau} \simeq 3{\cdot}10^{17}$, and random variation of satellite acceleration should be

$$\delta\alpha_{IJT} \simeq \frac{m_{ion} v \sqrt{N_{\tau}}}{M_{\Sigma}\tau} \simeq 5{\cdot}10^{-15}\text{cm/sec}^2. \qquad [8]$$

This equation is based on the assumption that ions do not create packs. The obtained numerical value of δa_{IJT} and the planned $(A_{GW})_{AC} \simeq 2{\cdot}10^{-15}$ cm/sec^2 indicate that noises in IJT (formed by packs of ions) may be a serious obstacle along the route toward the planned sensitivity.

b. Thermal Radiation Pressure and the Gray Factor Roles. Thermal radiation (i.e., Stefan–Boltzmann's law) may produce relatively strong AC acceleration of RM due to random variations of entourage (envelope) temperature δT_{AC}

$$(\alpha_{RM})_{AC} \simeq \xi \frac{4S\sigma_{SB}T^3\delta T_{AC}}{m_{RM}C} \qquad [9]$$

where ξ is the gray factor, σ_{SB} is the Stefan–Boltzmann constant, T is the mean temperature of the entourage, c is the speed of light, and S is the square of the RM cross-section. For ideal black body $\xi = 1$, for the real material of the entourage ξ is smaller than unity. If $T = 300$ K, $S = 15$ cm^2, and $m_{RM} = 10^3$ g, to satisfy the condition $(a_{RM})_{AC} < (A_{GW})_{AC} = 2{\cdot}10^{-15}$ cm/sec^2, it is necessary to perform thermal isolation of the envelope to have $\delta T_{AC} < 5{\cdot}10^{-7}$ K.

The gray factor ξ also may depend on temperature $(1/T){\cdot}(\partial\xi/\partial T) \neq 0$. Simple calculations (omitted here) give the following numerical estimate: if $(1/T){\cdot}(\partial\xi/\partial T)$ is not substantially different from the Young modulus ordinary temperature dependence [i.e., $(1/T){\cdot}(\partial Y/\partial T) \simeq 10^{-5}$ K^{-1}], then δT_{AC} should be smaller than 10^{-3} K.

Simple calculations (also omitted here) show that thermal equilibrium fluctuations (i.e., $\sqrt{\delta T^2_{equilibr}} = \sqrt{k_B T^2 C_V^{-1} V^{-1}}$, where C_V is the specific heat capacity, and V is the envelope part volume) in the parts of the envelope will be substantially smaller than the numerical estimates presented above (at the level of 10^{-10} to 10^{-11} K) and thus may be not taken into account.

c. Density Inhomogeneity of RM. Assuming that RM will have a spherical shape and that several narrow laser beams will "touch" the RM surface, and with detectors these beams will act as shadow sensors, which will control the IJTs, then the experimentalists will be confronted with an undesirable effect: modulation of the input signal from sensors due to RM rotation. This effect will inevitably appear due to inhomogeneity of the RM density. The typical value of density inhomogeneity in metals and metal alloys is $\Delta\rho/\rho \simeq 10^{-4}$. Thus, it is evident that gravitational center of mass (that the RM rotates around) will be shifted from the geometrical center by $\approx 2{\cdot}10^{-4}$ cm (if $r_{RM} = 2$ cm). If RM is manufactured with the same accuracy as the RM of the Gravity Probe B (i.e., $\Delta r/r \simeq 10^{-6}$), and if the laser beam shadow sensor thickness near the "touching" zone is $D = 2{\cdot}10^{-3}$ cm, then the modulation of the laser power due to this rotation has to be at the level of 10%. Rotation of the RM may appear either due to the initial kick or due to possible rotational instability (26).

The three listed above effects (obstacles), which have to be taken into account, probably are not the last ones. The only "remedy" to avoid missing other undesirable effects is the terrestrial laboratory test at least with the one-dimensional model.

IV. The Role of Cosmic Rays and of Charging Effect in LIGO and LISA Projects

The mirrors in Advanced LIGO will be manufactured of very pure fused silica SiO_2, and each of them will have diameter $2R \simeq 35$ cm and height $H \simeq 20$ cm. Thus, the total $m_p \simeq 4{\cdot}10^4$ g. The certain part of all cascades (showers) generated by very high energy muons will pass through the mirror at a small angle to the FP resonator axis. Thus, a fraction $\Delta\mathscr{E}$ of the total cascade energy $\mathscr{E}$ passing through 20 cm of fused silica will be lost in the mirror bulk. At sea level, one may estimate the "pace" of such "passes": one event per 2 weeks with $\mathscr{E} \simeq 1$ TeV $= 1.6$ erg and $\Delta\mathscr{E} \simeq 120$ GeV, and one event per 3 months with $\mathscr{E} = 2$ TeV and $\Delta\mathscr{E} \simeq 230$ GeV. The lost energy $\Delta\mathscr{E}$ transfers a momentum to the mirror and causes its displacement $\Delta x_M \simeq \Delta\mathscr{E}\tau/(m_p c)$ (c is the speed of light). The main part of $\Delta\mathscr{E}$ will create a hot spur in the mirror bulk. Due to nonzero thermal expansion factor of SiO_2, this spur will distort the mirror and thus create a height shift ΔH averaged over the laser beam area. The calculations (see details in ref. 27) show that ΔH can be $8{\cdot}10^{-17}$ cm once per few months (i.e., easy to be recorded by Advanced LIGO). In essence, these rare "jumps" are not dangerous for Advanced LIGO because a veto rule may be used (LIGO has two antennae).

A more serious effect that indeed creates a noise floor in Advanced LIGO and the Post Advanced LIGO antennae is much more frequent low-energy muons of cosmic origin. At the altitude of 500 m above the sea level, an experimentalist should expect ≈ 20 muons per sec hitting the mirror (within the energy range 0.2 GeV $< \mathscr{E} <$ 2 GeV). Calculations (omitted here) show that there is a big gap (>3 orders) between the SQL of LIGO sensitivity and this noise floor (see details in ref. 28).

In 1995, R. Weiss (29) pinpointed the potential danger from electric charge accumulated on the mirror surface. Recently, V. P. Mitrofanov and his colleagues (30, 31) measured the value of electric charge density σ on a model of LIGO mirror suspended on thin fused silica fibers in high vacuum chamber. The net result of these measurements is that σ_{DC} may be as high as 10^6 to 10^7 electrons per cm^2 and that $d\sigma/dt$ is not zero: the monotonic rise of negative electric charge density at the level of $d\sigma/dt \simeq 10^5$ electrons per cm^2 per month was observed. O. G. Ryazhskaya (see ref. 27) found an explanation for this new effect. The origin is the difference of atomic number of solid that the vacuum chamber is made of and the atomic number of the mirror material itself. Ryazhskaya also predicted the value of rare bursts of electrons, which may be "trapped" by the mirror. Thus, these two effects (DC and AC components of σ) may create a relatively strong Coulomb force kick between the mirror and its grounded entourage.

It is very likely that charging effect in the LISA project will have an even more important role than in LIGO (because of the much smaller value of acceleration to be measured and much longer averaging time in LISA). Recently, H. M. Araújo and colleagues (32) presented a very important analysis of this effect. I regard this analysis as a first approximation to the complete list of recommendations for experimentalists. First of all, it is necessary to take into account the potential possibility to choose different materials for the RM and its envelope and to take into account O. G. Ryazhskaya's predictions (27). However, at present the cubic shape of the RM together with capacity readout sensors evidently seems to me very unattractive because the RM becomes statically unstable due to potentially accumulated electric charge.

V. Conclusion

There are two more experimental programs with PMs that should be added to the above-described LIGO and LISA. The first one, which has recently brought very impressive results, may be called PM with clock. A stable clock (secondary frequency standard) was a part of the Cassini Deep Space Network mission. The clock was based on a high-quality factor (i.e., $Q_{\mathrm{em}} > 10^9$) whispering gallery mode microwave resonator made of very pure sapphire with Allan frequency deviation of $\Delta\omega_{\mathrm{em}}/\omega_{\mathrm{em}} \simeq 10^{-15}$ during $\tau \simeq 10^3$ sec and very low phase noise. This clock has permitted B. Bertotti and colleagues (33) to verify the validity of General Relativity with relative uncertainty up to 10^{-5}.

PM with clock may be improved substantially using the empirical rule discovered in 1987: the purification of sapphire crystal brings very substantial rise of Q with decrease of thermostat temperature (34). The SQL of resonator frequency relative deviation is

$$\left(\frac{\Delta\omega_{em}}{\omega_{em}}\right)_{\mathrm{SQL}} \simeq \sqrt{\frac{\hbar}{YV\tau}} \qquad [10]$$

for optimal power

$$W_{\mathrm{optim}} \simeq \frac{YV\omega_{\mathrm{em}}}{Q_{\mathrm{em}}^2}, \qquad [11]$$

where Y is the Young modulus, V is the resonator volume, τ is the averaging time, and ω_{em} is the resonance frequency (35, 36). For $V \simeq 3{\cdot}10^3$ cm^3, $Y = 4{\cdot}10^{12}$ erg/cm^3, and $\tau \simeq 10^3$ sec, the value of $\Delta\omega_{\mathrm{em}}/\omega_{\mathrm{em}} \simeq 10^{-23}$, i.e., 6 orders smaller than the best existing today microwave clock frequency stability. To "get" such a clock it is "only" necessary to increase Q_{em} up to 10^{12} (see details in ref. 28).

The second program of experiments with PMs, which also has clock, was proposed by M. V. Sazhin (37) and was based on use of the pulsar timing, i.e., "natural" clock (see also ref. 38). This method may allow the detection of low-frequency GW [$\omega_{\mathrm{GW}} \simeq 2\pi{\cdot}(10^{-7}$ to $10^{-9})$ sec^{-1}]. A program of such searches is in the process of development. In this program, it is expected that one will be able to detect GWs from double supermassive black holes at cosmological distances and also to detect stochastic GWs of cosmological origin (see details in ref. 39). In this program, 40-msec pulsars will be used.

Today there is another experimental program with PM. This program was initiated by Charles H. Townes and his colleagues from the University of California at Berkeley (40). The key idea of this program is to use a star as PM and a very high angular resolution telescope Infrared Spatial Interferometer (ISI) as a meter to detect the changes (distortions) of the star itself. The initial test model (a very inexpensive one) has already demonstrated high resolution and unexpected PM features.

Summing up this short review, it is possible to predict that this area of experimental physics will give a lot of qualitatively new astrophysical information.

1. Braginsky VB (1968) *Sov Phys JETP* 26:831.
2. Braginsky VB, Vorontsov YI, Khalili FY (1977) *Sov Phys JETP* 46:705.
3. Thorne KS, Drever RWP, Caves CM, Zimmermann M, Sandberg VD (1978) *Phys Rev Lett* 40:667–671.
4. Braginsky VB, Vorontsov YI, Khalili FY (1978) *JETP Lett* 27:277.
5. Unruh WG (1978) *Phys Rev D* 18:1764–1772.
6. Grangier P, Levenson JA, Poisat J-P (1998) *Nature* 396:537–542.
7. Nogues G, Rauschenbeutel A, Osnaghi S, Brune M, Raimond JM, Haroche S (1999) *Nature* 400:239–242.
8. Barton G (1991) *J Phys A* 24:991–1005.
9. Braginsky VB, Khalili FY (1991) *Phys Lett A* 161:197–201.
10. Weber J (1960) *Phys Rev* 117:306–313.
11. Barish B, Weiss R (1999) *Phys Today* 52:44–50.
12. Abbott B, Abbott R, Adhikari R, Ageev A, Agresti J, Allen B, Allen J, Amin R, Anderson SB, Anderson WG, *et al.* (2005) *Phys Rev D* 72:102004.
13. Abbott B, Abbott R, Adhikari R, Ageev A, Agresti J, Allen B, Allen J, Amin R, Anderson SB, Anderson WG, *et al.* (2005) *Phys Rev D* 72:082001.
14. Abbott B, Abbott R, Adhikari R, Ageev A, Agresti J, Allen B, Allen J, Amin R, Anderson SB, Anderson WG, *et al.* (2005) *Phys Rev D* 72:082002.
15. Abbott B, Abbott R, Adhikari R, Ageev A, Agresti J, Allen B, Allen J, Amin R, Anderson SB, Anderson WG, *et al.* (2005) *Phys Rev D* 72:062001.
16. Abbott B, Abbott R, Adhikari R, Ageev A, Agresti J, Allen B, Allen J, Amin R, Anderson SB, Anderson WG, *et al.* (2005) *Phys Rev D* 72:042001.
17. Abramovici A, Althouse W, Camp J, Durance D, Giaime JA, Gillespie A, Kawamura S, Kuhnert A, Lyons T, Raab FJ, *et al.* (1996) *Phys Lett A* 218:157–163.
18. Braginsky VB, Gorodetsky ML, Vyatchanin SP (1999) *Phys Lett A* 264:1–10.
19. Braginsky VB, Mitrofanov VP, Tokmakov KV (1996) *Phys Lett A* 218:164–166.
20. Imshennik V, Popov I (1998) *Astron Lett* 24:206–221.
21. Braginsky VB, Gorodetsky ML, Khalili FY, Thorne KS (2000) *Phys Rev D* 61:044002.
22. Danilishin SL, Khalili FY (2006) *Phys Rev D* 73:022002.
23. Braginsky VB (2005) *Physics Uspekhi* 48:595–600.
24. Heinzel G, Braxmaier C, Danzmann K, Gath P, Hough J, Jennrich O, Johann U, Rüdiger A, Sallusti M, Schulte H (2006) *Classical Quant Gravity* 23:S119–S124.
25. Danzmann K, Rüdiger A (2003) *Classical Quant Gravity* 20:S1–S9.
26. Braginsky VB, Manukin AB (1970) *Sov Phys JETP* 11:321.
27. Braginsky VB, Ryazhskaya OG, Vyatchanin SP (2006) *Phys Lett A* 350:1–4.
28. Braginsky VB, Ryazhskaya OG, Vyatchanin SP (2006) *Phys Lett A* 359:86–89.
29. Weiss R (June 6, 1995) *Note on Electrostatics in the LIGO Suspensions* (California Institute of Technology, Pasadena, CA), LIGO Document T960137-00-E. Available at www.ligo.caltech.edu/docs/T/T960137–00.pdf.
30. Mitrofanov VP, Prokhorov LG, Tokmakov KV (2002) *Phys Lett A* 300:370–377.
31. Mitrofanov V, Prokhorov L, Tokmakov K, Willems P (2004) *Classical Quant Gravity* 21:S1083–S1089.
32. Araújo HM, Wass P, Shaul D, Rochester G, Sumner TJ (2005) *Astroparticle Phys* 22:451–469.
33. Bertotti B, Iess L, Tortora P (2003) *Nature* 425:374–376.
34. Braginsky VB, Ilchenko VS (1987) *Phys Lett A* 120:300–305.
35. Braginsky VB, Vyatchanin SP (1978) *Sov Phys JETP* 74:828.
36. Braginsky VB, Panov VI, Vyatchanin SP (1979) *Sov Phys Dokl* 247:583.
37. Sazhin MV (1978) *Sov Astron* 22:36.
38. Detweiler S (1978) *Astrophys J* 234:687–693.
39. Jenet FA, Hobbs GB, Lee KJ, Manchester RN (2005) *Astrophys J* 625:L123–126.
40. Hale DDS, Bester M, Danchi WC, Fitelson W, Hoss S, Lipman EA, Monnier JD, Tuthill PG, Townes CH (2000) *Astrophys J* 537:998–1012.
41. DeBra DB (1997) *Classical Quant Gravity* 14:1549–1555.