International School on Gravitation and Cosmology: Course 10 "Gravitational Measurements, Fundamental Metrology, and Fundamental Constants"[1] (Erice, Sicily, May 2–12, 1987)

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The "International School on Gravitation and Cosmology" is one of 70 different schools organized and financed by the E. Majorana Center "Scientific Culture" in Italy. The director of the center is Professor A. Zichichi and the director of the school is Professor V. de Sabbata.

The school's director invites well-known specialists from different countries to give the various courses. Courses on gravitation and cosmology had in the past been directed by J. Weber, P. Bergmann, N. Rosen, E. Schmutzer, and others.

The tenth course of the gravitation and cosmology school on the subject "Gravitational measurements, fundamental metrology, and fundamental constants" was held on May 2–12, 1987 in Erice, Sicily. The director of the course was V. N. Mel'nikov, a member of the staff of the State Committee on Standards (SCS) of the Council of Ministers of the USSR. Soviet lecturers also included R. N. Faustov, V. P. Shelest (SCS) and Yu. M. Loskutov and V. N. Rudenko [Moscow State University (MSU)].

Among foreign lecturers, we single out such well-known scientists as J. Weber (Maryland University), R. Drever (Caltech), R. Bergman (New York University), E. R. Cohen (Science Center of the Rockwell International Corporation—all from the USA, and N. Rosen (Technological Institute, Haifa, Israel). E. Fischbach, G. Gillies, R. Hellings, R. Reasenberg (USA), J. Picella, F. Ricci, J. Prodi (Italy), E. Braun and E. Knabe (West Germany), U. Takano and N. Tanaka (Japan), and others also participated. There were 50 participants, including students, in all.

The main themes of the school were gravitational-relativistic metrology (high-precision space-time and gravitational measurements), quantum metrology, and fundamental physical constants. Attention was devoted primarily to problems such as 1) gravitational-relativistic models for synchronization of time and frequency standards; 2) gravitational-relativistic models for astronomical measurements (**"RSDB"**, [Russian acronym for VLBI?], pulsar scale, telemetry); 3) theories admitting variation of the fundamental constants; 4) measurements of the gravitational constant, its possible dependence on time, distance, composition, etc., and the idea of the "fifth force"; 5) gravitational-wave detectors (solid-state and laser interferometric detectors); 6) gravitational-relativistic effects in the solar system, new projects and technology of gravitational measurements; 7) fundamental physical constants, theory and experiment, their agreement and check of quantum electrodynamics; 8) quantum Hall effect and other macroscopic quantum effects, promising quantum standards for electrical units; 9) metrological aspects of the physics of high energy densities.

Soviet specialists each gave two or three lectures: V. N. Mel'nikov, "Gravitational-relativistic metrology" and "Problems of the coupling and possible variations of the fundamental physical constants"; V. N. Rudenko, "Seismographic detection of gravitational waves," "Optoacoustic gravitational antenna," and "Methods of quantum nondemolition measurements for optical gravitational antennas"; Yu. M. Loskutov, "Relativistic theory of gravitation"; R. N. Faustov, "Quantum electrodynamics and the fundamental constants"; and, V. P. Shelest, "Introduction to the physics of high energy densities."

We shall discuss the most important lectures given at the school and call attention to new results and trends.

1. METROLOGY

1.1. The lectures in this section were presented by Professor E. R. Cohen (Science Center, Rockwell International Corporation, USA). He described the results of work performed by the International Metrological Commission CODATA on the coordination of the fundamental physical constants in 1986. The final tables of the numerical values of the constants with an indication of the measurement error up to 1986, inclusively, are of interest. The tables are given in the bulletin of CODATA and will be published in the proceedings of the school. For most atomic constants the errors correspond to calculations in sixth-eighth order perturbation theory. The least accurately determined constant remains the gravitational constant (the error occurs in the fourth significant figure).

1.2. The lecture by E. Braun (Physicotechnical Institute, Braunschweig, West Germany) concerned the development of new standards for electrical units—the ohm and the volt—based on the quantum Hall and Josephson effects. The standards developed in West Germany still do not satisfy the necessary metrological requirements and can be employed only for calibrating traditional standards.

2. MEASUREMENT OF THE GRAVITATIONAL CONSTANT AND RELATIVISTIC EFFECTS IN THE SOLAR SYSTEM

The numerical value $G = (6.67259 \pm 0.00085) \times 10^{-11}\ m^3kg^{-1}\ sec^{-2}$, has been adopted in CODATA i.e., the error occurs in the fourth significant figure.

2.1 G. Gillies (University of Virginia, USA) reported on a new apparatus (updating of the well-known apparatus of J. Beams) for measuring G with an accuracy of $1\cdot 10^{-5}$. The apparatus is a modification of the Cavendish experiment employing magnetic suspension of the test masses, placed on a uniformly rotating platform. Most of the effort went into ensuring a high degree of uniformity of the rotation, so that $\dot{\omega}/\omega \approx 10^{-20}\ h^{-1}$. The apparatus cost 1.5 million dollars. It permits recording a variation of the mass of the rotating test body of $\dot{m}/m \approx 5\cdot 10^{-12}\ yr^{-1}$. At the present time this is the only system in the world for measuring the absolute value of G with an accuracy up to five significant figures. It is also intended for measuring time variations $\dot{G}/G \sim 10^{-10}$–$10^{-12}\ yr^{-1}$. Experiments on observing the anomalous spin interaction of magnetic moments of electrons are also being conducted. It is assumed that this tensor interaction is of the dipole-dipole type. A torsion pendulum is employed. Large attracting masses have $2 \cdot 10^{23}$ polarized electrons; small attracted masses have ten times fewer polarized electrons. The shift of the period accompanying a change in the polarization of a pair of masses is measured. Nineteen series of measurements were performed in a period of 1200 hours. The ratio of the anomalous spin interaction (tensor) to the interaction of magnetic moments turned out to be equal to $\alpha = (-0.45 \pm 3.7) \cdot 10^{-10}$.

2.2. E. Fischbach (Washington University, USA) presented three lectures on the hypothetical "fifth force"—a new type of interaction of test masses, which could be equivalently described in terms of spatial variations of the gravitational constant $G(r)$. The results of the latest experiments along these lines, performed in the USA, have already been published in Physical Review Letters (March, 1987). The new experiments reported by Fischbach reduce to modifications of Cavendish's experiment so as to make a high-precision check of the gravitational law at distances of 50-1000 meters. In this range the existing experimental data permit giving only a very rough limit on the magnitude of the possible deviation from Newton's law—less than 10^{-3} of the Newtonian force. In particular, Tiberger's result in an experiment with a mountain were reported. It was found that $|\alpha\lambda| \approx 1.2$–$0.4$ m in agreement with Stacey's experiments in mine shafts.

Another experiment (Stubbs *et al.*) with four suspended masses (two copper and two beryllium) showed a discrepancy with the preceding estimates:

$$|\alpha\lambda| < 0.1 \text{ m}.$$

His results [Phys. Rev. Lett. **58**, 1070 (1987)] are analyzed. Since according to a repeat analysis of Eötvös experiments the effect depends on the composition, the discrepancies are probably associated with this: $\alpha = \alpha(B/\mu)$. Multicomponent models with a different dependence of the fifth force on the charges B, L, N, and Z and the corresponding experimental verifications are needed.

Data from the new experiments at the beginning of 1988 remain contradictory: most of the laboratory experiments do not agree with mine-shaft experiments. They are explained with the help of theoretical models with the fifth force depending on both the baryon charge and on the isospin and even on the number of quarks.

2.3. R. Reasenberg (Massachusetts Institute of Technology, Cambridge, USA) lectured on the status of the well-known American project POINTS—optical interferometer consisting of four high-precision optical telescopes on a rigid two-meter platform orbiting the earth. The project is now on the drawing boards; laboratory experiments exploring the properties of materials for the carrying platform are being performed (at MIT). The project has three ambitious goals: a) search for other planetary systems within the galaxy; b) checking GTR in second order in the weak field parameter $\sim(\varphi/c^2)^2$ (deflection of a light beam in the sun's field by 11 angular μsec); c) intergalactic astrometry and measurement of the Hubble constant with an accuracy of not worse than 10%. The intrinsic accuracy of the project in making angular measurements of distant stars corresponds to measurement of an angle $\sim\pi/2$ with an error of $\sim 10^{-6}$ angular seconds; the current accuracy of optical measurements reaches only $\sim 10^{-2}$ angular seconds. Although the project was initiated by I. Shapiro's group at MIT, of which the lecturer is a member, other groups have now been added to it: the list includes 16 scientists from different scientific centers in the USA. It is anticipated that in the project a new technology guaranteeing that the systems for orienting and stabilizing the carrier platform will meet stringent requirements will be developed, and the project is thus undoubtedly of practical value. There is as yet no concrete data on the financing of this project and its inclusion in NASA's program.

2.4. In his lectures R. Hellings (Jet Propulsion Laboratory, Pasadena, USA) discussed the use of data on high-precision radar measurements on planets in the solar system and space stations in order to evaluate time variations of the gravitational constant. A new, more precise analysis of the Viking data confirmed the now three-year-old estimate $\dot{G}/G \lesssim (0.2 \pm 0.4) \cdot 10^{-11}$ yr^{-1}. Hellings reported on plans for work to be performed jointly with specialists at the Institute of Space Research of the USSR Academy of Sciences employing a possible relay on Phobos. Tracking with the help of relays the evolution of Phobos' orbit relative to Mars, according to estimates by Hellings, will give $\dot{G}/G \lesssim 16 \cdot 10^{-13}$ yr^{-1} with an observation time of one year and $\dot{G}/G \lesssim 8 \cdot 10^{-13}$ yr^{-1} with observations over a period of five years. The problem of performing accurate measurements of the time intervals in relativistic experiments in connection with the use of different reference systems was also discussed in the lectures. Based on the data presented in these lectures, hydrogen standards in systems for measuring frequency variations with a stability of $\Delta f/f \sim 10^{-13}$–10^{-14} over a time of $\tau \sim 10^3$ sec, are currently employed on NASA's space communication stations; the accuracy of the measurement of velocity variations is $\delta v \sim 0.01$ cm/sec.

2.5. N. Krishnan (Tata Institute, Bombay, India) reported on the development of a laboratory apparatus for measuring spatial variations of the gravitational constant. The same setup is intended for checking the principle of equivalence of inertial and gravitational masses with an error of 10^{-14}, which is two orders of magnitude better than the results of the experiments of Braginskiĭ and Panov (MSU, 1971). The procedure of the Indian experiment is analogous to that of the MSU experiment; an improvement of the sensitivity is expected owing to the use of forced parameters of a torsional suspension; the mass is ~ 200 g and the relaxation time equals $5 \cdot 10^8$ sec; the proposed measurement time is 20–30 days.

2.6. Dr. J. A. Prodi (Trento University, Italy) described a terrestrial experiment, proposed and realized under the direction of M. Serdonio and S. Vitale, on the detection of the entrainment of the Lense-Thirring inertial reference systems owing to the rotation of the earth. The method is to compare the astrometrical measurements of the earth's rotation and the inertial measurement of the angular velocity in a laboratory. It is proposed that the result will be achieved by developing a dynamic detector of local angular velocity based on a new principle—a gyromagnetic electron gyroscope (GEG), which does not contain any mechanical moving structures. The GEG consists of a superconducting screen surrounding a ferromagnetic rod, whose magnetization is measured with a SQUID. Its operation is based on the gyromagnetic effect, i.e., the difference in the gyromagnetic ratios of Cooper pairs in the superconductors and electron spins in the magnetic rod, respectively. The measurement accuracy required for the experiment ($\sim 3\%$) has already been achieved in the "**VLBI**" technology. A theory of the GEG experiment is given. Experiments with GEG are now being performed.

3. GRAVITATIONAL-WAVE EXPERIMENT

Representatives of three research centers studying the problem of searching for gravitational waves were present at the school.

3.1. J. Weber (Maryland University, USA)—one of the founders of this research and director of the work on gravitational antennas at Maryland University—reported that an elevated noise level correlated in time with the burst of the Supernova 1987 was recorded on one of the gravitational antennas. The antenna operated at room temperature and had a sensitivity of $\Delta l/l \sim 10^{-16}$ in a frequency band $\Delta f \sim 10$ Hz. The data were not fully analyzed, and the statistical probability of the event was not evaluated. In his lectures J. Weber reported the possibility of reinterpreting and recalculating the absorption cross section of a resonant gravitational antenna taking into account collective coherent processes at the molecular level; he considered at the same time the calculation of the absorption cross section for a neutrino flux. He has publicized these results previously, and the calculations have already been published (anniversary collection or works dedicated to Eddington, as well as a paper in the Foundations of Physics in 1986). These ideas, however, are not being supported by other specialists.

3.2. R. Drever (California Institute of Technology, Pasadena, USA) described the status of the construction at large laser-interferometric gravitational antennas "on free masses" with a baseline of 3–5 km. The cost of the project is ~ 40 million dollars per antenna. There are two antennas: one in California and the other near Boston (New England, Massachusetts) under the aegis of MIT. Professor R. Vogt (Caltech) has been named the director of the project; the final decision regarding the financing was expected at the end of 1987. The construction of an analogous antenna in Scotland with a shorter 1 km baseline and costing 3 million dollars, is also being planned; but the dates are not clear.

Professor Drever also reported on further improvement of the technological details of a small 40 meter model operating at Caltech. In 1984 this model had a sensitivity to the displacement of the test masses of $\sim 3 \cdot 10^{-15}$ cm over a period of 1 sec. At the present time the sensitivity has been increased to $8 \cdot 10^{-16}$ cm/Hz$^{1/2}$, the brass test masses were recently replaced with masses consisting of fused quartz with polished endfaces. The mirrors are held on the masses by molecular interaction forces, and there is no need for a gluing interlayer, which contributed excess noise. It is expected that the sensitivity will be improved by a factor of five and will reach the level $1.6 \cdot 10^{-16}$ cm/Hz$^{1/2}$; this means that the sensitivity of a large antenna to a perturbation of the metric in a frequency band of 1000 Hz will equal $h = \Delta l/l \sim 10^{-20}$.

3.3. J. Picella (Rome University and CERN, Geneva) repeated in his lecture the previously known information about the detection of an elevated noise background by the gravitational antenna in Rome prior to the burst of the supernova 1987. The energy expenditure at the center of the galaxy is estimated to be 2400 solar masses, which precludes a gravitational-wave explanation of the excitation (the antenna in Rome operated at room temperature). The antenna at CERN (Geneva), described in Nuovo Cimento (1986), has a sensitivity of $h \sim 10^{-17}$ in the 1000 Hz band, but it was not operating during the supernova burst.

Aside from participating in the school, we visited Rome University, the Center of Nuclear Research (CNR) in Frascati (V. N. Rudenko) and the neutron laboratory at Gran Sasso (V. N. Mel'nikov). The purpose of the visit was to learn about gravitational antennas of the Weber type, developed by Professor Amaldi's group (Rome University) and Professor F. Bordoni's group (CNR). The uncooled antenna at Rome University—a small model of CERN's antenna—is used for finalizing technical details, which are then transferred to the large antenna. Monitoring of the operation of the antenna and data analysis are performed entirely with American computer equipment. The antenna at CNR also has a small mass (400 kg), but it is cooled down to 4 K; the detection system consists of American made (Boulder, Colorado, USA) displacement transformer and a dc SQUID. Bordoni's group plans to work in the "coincidence-search" mode with the antenna at CERN.

In addition, on an experimental level Bordoni's group is actively developing quantum-nondemolition detection methods in experiments with simple bodies. In cooperation with Professor D. Douglass' group at Rochester University (USA) radioelectronic microwave systems (70 GHz), based on QND principles, are being studied in order to reduce their noise temperature to the quantum level $kT_m \approx \hbar\omega_\mu$, where $\omega_\mu \sim 10^{-4}$ is the frequency of the mechanical oscillations (of the gravitational detector) being measured. The best Japanese and American electronics, GaAs field-effect transistors operating at a temperature of 4 K, and SQUID-based parametric amplifiers are employed. A temperature of $T_m \approx 10^{-2}$ K has been achieved; 10^{-6}–10^{-7} K is required; construction work at Gran Sasso is proceeding at full speed; the tunnels are ready, and finishing work is being performed prior to installation of the measuring apparatus. Aside from neutrino detectors, installation of a gravitational antenna has been proposed for the future.

The next (11th) course will be given in Erice in 1989 on the subject "Quantum theory in curved space-time." Audretsch (West Germany) has been named the director.

[1] The lectures of the tenth course of the school were published by Reidel (the Netherlands) at the beginning of 1988 and were edited by V. N. Mel'nikov (USSR) and V. de Sabbata (Italy).

Translated by M. E. Alferieff