E. Yu. Aleshkina, G. A. Krasinskiĭ, E. V. Pit'eva, and M. L. Sveshnikov. *Experimental check of relativistic effects and evaluation of the magnitude of the change in the gravitational constant from observations of the inner planets and the moon.* The rapid development of the technology for performing positional observations of the planets over the last ten years has made it urgent to make a new check of relativistic effects in the motion of the inner planets and the moon. A substantially new element here is the introduction, in 1959, of the atomic time scale into astronomical practice, which has made it necessary to determine simultaneously the magnitude of the secular disagreement between the atomic time scale, in which the observations are performed, and the dynamic time scale, in which the equations of motion of GTR are valid. According to Canuto[1] the secular disagreement between these scales can be interpreted in terms of the variation of the magnitude of the gravitational constant G, expressed in atomic units of time. The directly observed effect in planetary longitudes depends on the time interval quadratically, as a result of which the quantity $\dot{G}/G$ is determined already with an error of the order of 10^{-11}/yr. This is exactly the level at which G is expected to vary, according to some physical arguments (for example, Dirac's large number hypothesis).[2] The observed effect is proportional to the orbital angular velocity and is largest for the moon. However, it is difficult to observe variations of G from lunar observations because of the fact that the secular decrease $\dot{n}_M$ of the mean angular velocity of the moon's orbital motion makes a contribution to the moon's longitude which is analogous in form but much larger in magnitude. This effect is due to terrestrial tides and cannot be predicted theoretically accurately enough. According to an idea of Van Flandern[3] this uncertainty can be determined from classical lunar observations of the 18th-20th centuries, performed in the universal time scale; the estimate of $\dot{n}_M$ obtained in this manner will not be distorted by the possible variations of G. However $\dot{n}_M$ can be determined from observations performed in the 18th-20th centuries only if the accuracy of the universal time scale is increased at the same time, which, in its turn, requires the use of planetary observations. Thus there arises a complicated complex of interrelated problems, whose solution requires the analysis of an enormous number of planetary and lunar observations, performed over the last two and a half centuries. The detailed execution of this program is still a task for the future, but some preliminary results have already been obtained. On the basis of the work performed in this program at the Institute of Theoretical Astronomy of the USSR Academy of Sciences a numerical theory of the motion of large planets and the moon in the interval 1715–2000 has been constructed, both modern planetary and lunar observations (radar and laser) and an extensive series of classical observations (meridians, passages of Mercury and Venus along the sun's disk, lunar eclipses) have been analyzed, and some results[4] on the experimental observation of the effects of GTR and the determination of the magnitude of $\dot{G}/G$ have been obtained. In particular, from an analysis of more than 5000 radar observations in 1961–1982 (performed, primarily, at the Institute of Radioelectronics of the USSR Academy of Sciences) the parameters of the PPN formalism,[5] which have turned out to agree with the GTR within the limits of their random errors, have been determined. For convenience we shall present the results, expressed below in terms of the observed deviation of the secular motion of the perihelion of Mercury from the theoretical value of GTR:

$$d\dot{\pi} = -0''.15 \pm 0''.12.$$

The good agreement with the predictions of GTR requires an explanation, since there exist modern data indicating that the sun has a nonzero quadrupole moment J_2. Namely, from an analysis of helioseismic observations Hill[6] obtained the value

$$J_2 = (5.5 \pm 1.5)\cdot 10^{-6},$$

which corresponds to an additional motion of Mercury's perihelion of 0″.7 per century, which contradicts the estimate of $d\dot{\pi}$ presented above. If Hill's data are confirmed, then this could indicate that the observations agree best not with GTR but rather with the PPN model with a parameter β whose value differs from unity:

$$\beta = 1.057 \pm 0.009.$$

Unfortunately the extremely sparse observational data on radar observations of Mercury (namely, the fact that there are no observations from 1965 to 1980) does not make our determination very reliable, in spite of the smallness of the formal estimate of the error involved.

We also derived $d\dot{\pi}$ from an analysis of all passages of Mercury across the sun's disk since 1723.[7] The best estimate obtained is

$$d\dot{\pi} = 0''.19 \pm 0''.33,$$

which is not nearly as good as the estimate presented above,

TABLE I. Determination of the variation in the gravitational constant $\dot{G}/G$ from observations (in units of 10^{-11}/yr).

Mercury	Venus	Mars	Weighted mean	General solution	Source
6,0 ± 4	6,0 ± 6	25,0 ± 33	6,2 ±3,3	15,0 ± 9	11
—	—	—	—	14,2 ± 1,2	12
—	—	—	—	0,2 ± 0,4	8
—0,9 ± 5,2	3,7 ± 0,8	16,1 ± 2,4	4,8 ± 2,0	4,1 ± 0,8ᵃ	4
—0,9 ± 5,2	3,8 ± 0,8	3,6 ± 2,4	3,7 ± 0,6	3,7 ± 0,8ᵇ	4
—2,6 ± 5,2	2,8 ± 0,6	13,4 ± 2,4	3,3 ± 1,8	3,1 ± 0,6ᵃ	This work
—1,2 ± 5,2	3,2 ± 0,6	3,1 ± 2,4	3,2 ± 0,5	3,1 ± 0,6ᵇ	

a) Theory of the Institute of Theoretical Astronomy b) JPL theory

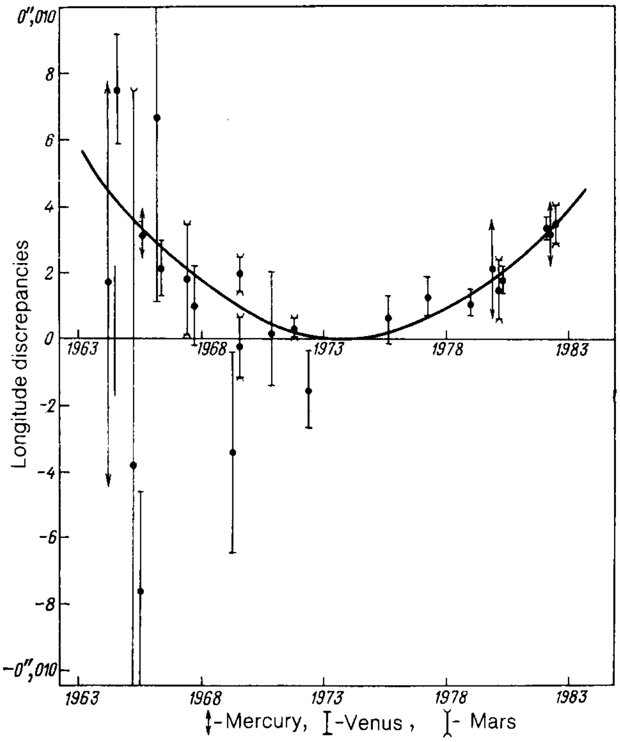

FIG. 1. Observed discrepancies in the longitudes of the planets owing to the secular variations of the gravitational constant G.

which was based on modern observations.

The combined analysis of radar observations yielded a statistically significant nonzero estimate for $\dot{G}/G$[4]

$$\frac{\dot{G}}{G} = (3.7 \pm 0.8) \cdot 10^{-11}/\text{yr}.$$

If the results are interpreted in accordance with Canuto's approach, then the sign of this quantity must be reversed. We performed the calculations twice—on the basis of the planetary theory, constructed at the Institute of Theoretical Astronomy, and on the basis of the theory of motion constructed at the Jet Propulsion Laboratory (JPL); the results turned out to depend slightly on the theory (see Table I, where the results obtained by other authors are also presented).

The data in the last two lines were obtained from a reanalysis of the results of Ref. 4 using the new observations of Venus performed in 1985.

We note that our results agree qualitatively with the American results, which were also obtained from radar observations (the first determinations gave unrealistically high values for $\dot{G}$, apparently as a result of the shortness of the time interval). We note, however, that preliminary results of the analysis of high-precision observations by Mariner-9 space probe and the Viking landers indicate that the deviation of $\dot{G}$ from zero is statistically insignificant (third row of Table I). In order to make a better judgment of the degree of reliability of our estimate of G, Fig. 1 shows the residual discrepancies in the planetary longitudes, arising without taking into account the secular variations of G. The parabola in Fig. 1 corresponds to the value $\dot{G}/G = 3.7 \cdot 10^{-11}$/yr. The parabolic trend in the discrepancies is quite reliable, though the fact that it could be caused by systematic errors in the old observations (prior to 1966) has not been excluded.

We also tried to estimate $\dot{G}$ from an analysis of observations of lunar eclipses of the inner planets and Aldebaran, and also the solar eclipses since 1730, and in addition the time scale was preliminarily corrected based on the passages of Mercury and Venus across the solar disk. The results turned out to agree very well with the classical determination made by Spenser Jones,[9] but were inconsistent with a series of observations performed in recent years. We assume, however, that our estimate for $\dot{n}_M$ (in the UT time scale)

$$\dot{n}_M = -22''.9 \pm 0''.9$$

is the most accurate estimate of this type. Comparing it with the value of $\dot{n}_M$ derived from an analysis of the lunar laser observations[10] (on an atomic scale) we obtain the estimate

$$\frac{\dot{G}}{G} = (-0.5 \pm 0.5) \cdot 10^{-11}/\text{yr},$$

which, as one can see, does not agree with the estimate of $\dot{G}/G$ presented above. It should be kept in mind here that the method used to find $\dot{G}$ from lunar observations is very indirect and is therefore not very promising. On the contrary, one can expect with a high degree of confidence that in the next few years the accuracy with which $\dot{G}/G$ is determined from radar observations of the inner planets will be improved by approximately an order of magnitude.

[1]V. M. Canuto, S.-H. Hsieh, and J. R. Owen, Mon. Not. R. Astron. Soc. **188**, 829 (1979).
[2]R. A. M. Dirac, Proc. R. Soc. London, Ser. A **338**, 439 (1974).
[3]T. C. Van Flandern, "High precision earth rotation and earth-Moon dynamics: lunar distance and related observations," Proceedings of the 63rd Colloquium of IAU, Grasse, May 22-27, 1981, D. Reidel, Dordrecht, Holland (1982), p. 207.
[4]G. A. Krasinsky *et al.*, Symposium of IAU, No. 114, Leningrad (1985), p. 315.
[5]V. A. Brumberg, Relativistic Celestial Mechanics (in Russian), Nauka, M., 1972.
[6]H. A. Hill, R. J. Bos, and P. R. Goode, Phys. Rev. Lett. **49**, 1794 (1982).
[7]G. A. Krasinsky *et al.*, Astron. Astrophys. **145**, 90 (1985).
[8]R. W. Hellings *et al.*, Phys. Rev. Lett. **51**, 1609 (1983).
[9]H. Spencer Jones, Mon. Not. R. Astron. Soc. **99**, 541 (1939).
[10]J. O. Dickey, J. G. Williams, and C. F. Yolder, Ref. 3, p. 209.
[11]R. D. Reasenberg and I. I. Shapiro, Experimental Gravitation, Accad. Naz. dei Lincei, Rome, 1978, p. 71.
[12]J. D. Anderson *et al.*, Acta Astronaut. **5**, 43 (1978).

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