Scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the Academy of Sciences of the USSR (24–25 September 1986)

Usp. Fiz. Nauk **151**, 715–724 (April 1987)

A joint scientific session of the Division of General Physics and Astronomy and the Division of Nuclear Physics of the USSR Academy of Sciences was held on September 24 and 25, 1986 at the S. I. Vavilov Institute of Physics Problems of the Academy of Sciences of the USSR. The following reports were presented at the session:

September 24

1. *É. Zh. Godik and Yu. V. Gulyaev.* Physical fields of biological objects.

September 25

2. *V. K. Abalakin, G. I. Eroshkin, M. A. Fursenko, and A. A. Shiryaev.* Current aspects of the problem of fundamental astronomical constants.
3. *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.

Summaries of two reports are presented below:

V. K. Abalakin, G. I. Eroshkin, M. A. Fursenko, and A. A. Shiryaev. *Current aspects of the problem of fundamental astronomical constants.* Astrometric studies are based on two elements, each of which relies on observations, performed by different (classical and new) measurement methods, i.e., on the fundamental catalog (for example FK4) and on the system of astronomical constants.

The fundamental catalog is the best approximation to the astronomical model of an inertial system, to which the positions of celestial objects and their motion can be referred. The coordinate axes of this system at a definite moment in time (epoch) are fixed by the positions and characteristic motions of the stars, presented in the fundamental catalog. To reduce astronomical observations performed at different points on the earth's surface, moving relative to the inertial reference system, i.e., to transfer them from one epoch to another and take into account all necessary astrometrical corrections, a certain set of numerical parameters, some of which are related to one another by theoretical relations, is required: the system of astronomical and geodesic constants. Thus among all parameters playing an important role in astronomy in general, the system of fundamental astronomical constants includes the numerical values of those which are associated with the theoretical and applied aspects of astrometry and ephemeris astronomy. Here the term "system" emphasizes the consistency of the numerical values adopted for the astronomical constants on the basis of accepted theories; in the system the basic constants, whose numerical values are determined independently based on observations, are distinguished from the derived constants, which are related to them theoretically. We note that the adopted values of the astronomical constants, because they must be consistent, are not always the best values from the standpoint of their accuracy.

In the course of astronomical investigations and the improvement of their experimental and theoretical foundations the following three standard systems of astronomical constants can be distinguished:

1) The system consisting predominantly of numerical values determined by the outstanding American theoretical astronomer S. Newcomb and adopted at two international conferences held in Paris in 1896 and 1911. This system of astronomical constants has been employed in all astronomical institutions in the world for more than 60 years.

2) In 1950 at the Paris conference on astronomical constants it was decided that Newcomb's system should be left almost unchanged and that the ephemeris time—the uniform time of Newtonian dynamics— should replace the universal time as an argument in the theories of the motion of the moon and planets and the corresponding ephemerides.

In 1963, at the 21st IAU Symposium in Paris a proposed new system of astronomical constants was examined, and in 1964 at the 12th General Assembly of the IAU in Hamburg the IAU (1964) System of Astronomical Constants was adopted and it was recommended that the system be introduced into astronomical practice starting in 1968.

3) Rapid progress in new observational methods and practical requirements with regard to higher accuracy of the ephemerides once again led to a reexamination of the numerical values of the constants and the structure of the IAU (1964) System of Astronomical Constants. A new system, prepared at the 9th Colloquium of IAU (Heidelberg, 1970), was adopted by the General Assembly of the IAU in 1976 in Grenoble and with some additions was endorsed by the General Assembly of the IAU in Montreal in 1979; the IAU (1976, 1979) System of Astronomical Constants was thus recommended for general use.

IAU (1976, 1979) system of astronomical constants

The units "meter" (m), "kilogram" (kg), and "second" (s) are the units of measurement of length, mass, and

0038-5670/87/040341-05$01.80

time in the International System of units (SI).

The astronomical unit of time is the time interval equal to 1 day (D, d) or 86 400 s. The time interval of 36 525 days equals one Julian century.

The astronomical unit of mass is the mass of the sun (S).

The astronomical unit of length (distance) is the length (A) for which the Gaussian gravitational constant (k) assumes a value equal to 0.017 202 098 95, using the astronomical units of length, time, and mass. The dimensions of k^2 are identical to those of the Newton-Cavendish gravitational constant G, i.e., $L^3M^{-1}T^{-2}$. The length A is also called the "unit distance."

Defining constant

1. Gaussian gravitational constant:
   $k = 0.017\,202\,098\,95$.

Primary constants

2. Velocity of light:
   $c = 299\,792\,458$ m sec^{-1}.
3. Light time for unit distance:
   $\tau_A = 499\,004\,782$ s.
4. Equatorial radius of the earth:
   $a_e = 6\,378\,140$ m.
5. Dynamical coefficient in figure of the earth:
   $J_2 = 0.001\,082\,63$.
6. Geocentric gravitational constant:
   $GE = 3.986\,005 \cdot 10^{14}$ m^{3}s^{-2}.
7. Newton-Cavendish gravitational constant:
   $G = 6.672 \cdot 10^{-11}$ m^{3}kg^{-1} sec^{-2}.
8. Moon/earth mass ratio:
   $\mu = 0.012\,300\,02$.
9. General precession in longitude per Julian century at the standard epoch 2000.0:
   $p = 5029''.0966$.
10. Inclination of ecliptic to equator at standard epoch 2000.0:
    $\varepsilon = 23° 26' 21''.448$.
11. Nutation constant at standard epoch 2000.0:
    $N = 9''.2025$.

Derived constants

12. Unit distance:
    $c\tau_A = A = 1.495\,978\,70 \cdot 10^{11}$ m.
13. Parallax of sun:
    $\arcsin(a_e/A) = \pi_\odot = 8''.794\,148$.
14. Aberration constant for standard epoch 2000.0:
    $\varkappa = 20'.495\,52$.
15. Ellipticity of the earth:
    $\alpha = 0.003\,352\,81 = 1/298.257$.
16. Heliocentric gravitational constant:
    $A^3k^2/D^2 = GS = 1.327\,124\,38 \cdot 10^{20}$ m^3·sec^{-2}.
17. Sun/earth mass ratio:
    $(GS)/(GE) = S/E = 332\,946.0$.
18. Mass ratio of sun and earth-moon system:
    $(S/E)/(1+\mu) = 328\,900.5$.
19. Mass of sun:
    $(GS)/G = S = 1.989\,1 \cdot 10^{30}$ kg.

The system of planetary masses

20. Sun/planet mass ratios:

Mercury	6 023 600	Saturn	3 498.5
Venus	408 523.5	Uranus	22 869
Earth + Moon	328 900.5	Neptune	19 314
Mars	3 098 710	Pluto	3 000 000
Jupiter	1 047.355		

21. Masses of planets in SI (kg):

Mercury	$3.3022 \cdot 10^{23}$	Jupiter	$1.8992 \cdot 10^{27}$
Venus	$4.8690 \cdot 10^{24}$	Saturn	$5.6856 \cdot 10^{26}$
Earth + Moon	$6.0477 \cdot 10^{24}$	Uranus	$8.6978 \cdot 10^{25}$
Earth	$5.9742 \cdot 10^{24}$	Neptune	$1.0299 \cdot 10^{26}$
Moon	$7.3483 \cdot 10^{22}$	Pluto	$7 \cdot 10^{23}$
Mars	$6.4191 \cdot 10^{23}$		

22. Equatorial radii of planets in SI (km):

Mercury	2 439	Jupiter	71 389
Venus	6 052	Saturn	60 000
Earth	6 378.140	Uranus	25 400
Mars	3 397.2	Neptune	24 300
Moon	1 738	Pluto	2 500
Sun	696 000		

The IAU (1976, 1979) System of Astronomical Constants is accompanied by the following system of geodesic parameters, endorsed by the International Geodesy Association in 1967 in Lucerne:

$$\begin{array}{rlrcl}
GE = & 398\,600.5 \cdot 10^9\ \text{m}^3\,\text{s}^{-2}, & J_1 & = & 108\,263 \cdot 10^{-8}, \\
Gm_{aTM} = & 3.5 \cdot 10^8\ \text{m}^3\,\text{s}^{-2}, & J_3 & = & -254 \cdot 10^{-8}, \\
a_e = & 6\,378\,140\ \text{m}, & J_4 & = & -161 \cdot 10^{-8}, \\
\alpha = & 1/298.257, & J_5 & = & -23 \cdot 10^{-8}; \\
g_e = & 978\,032 \cdot 10^{-5}\ \text{m} \cdot \text{s}^{-2}, & J_6 & = & 54 \cdot 10^{-8}, \\
\omega = & 7.292\,115 \cdot 10^{-5}\ \text{s}^{-1}, & R_0 & = & 6\,363\,676\ \text{m}. \\
W_0 = & 6.263\,683 \cdot 10^7\ \text{m}^2\,\text{s}^{-2} & & &
\end{array}$$

W_0 is the numerical value of the gravitational potential at the 1976 IAU geoid and R_0 is the scale factor for the geopotential.

However, in accordance with the resolutions ratified at the 17th General Assembly of the International Geodesy and Geophysics Union, held in 1979 in Canberra, a new geodetic reference system was introduced in 1980, in which, in particular, the following values were adopted: $a_e = 6\,378\,137$ m, $GE = 398\,600.47 \cdot 10^9$ m^3·s^{-2}, and $W_0 = 6.263\,686 \cdot 10^7$ m^2·s^{-2}. The numerical values of the rest of the parameters were left unchanged (or were changed by unity in the last decimal place: $J_6 = 55 \cdot 10^{-8}$, $g_e = 978\,033 \cdot 10^{-5}$ m·s^{-2}).

Together with the new IAU (1976, 1979) System of Astronomical Constants a new theory of motion of the large planets in the solar system and the moon DE 200/LE 200, based on the relativistic equations of motion, a new IAU (1980) theory of nutation, new precession formulas, new time scales—barycentric dynamic time TDB, argument in the theories of planetary and lunar motions (coordinate time in the terminology of GTR), and terrestrial dynamic time TDT, argument of the corresponding ephemerides, also used for fixing the moments of observations (proper time), were introduced into astronomical research. A distinguishing feature of the new system is, as one can see from the table, that the SI system of units was introduced into it; more precisely, in fundamental astronomy only the units of length (distance) and time are employed, since the mass always enters in the form of a product by the Cavendish gravitational constant G, whose dimensions are L^3T^{-2}.

Thus at the present time the problem of astronomical constants is linked with several complicated questions of both theoretical and practical nature, referring to the measurement of time and distances.

It should be noted, first of all, that any SI unit is a proper unit in the sense of the theory of relativity, since it is determined by a local physical process, SI units therefore cannot be regarded as universal in different reference systems. For example, when one is talking about the terrestrial reference system, the unit of time is the SI second, also adopted as a unit in the atomic time system TAI, defined on a level surface (on a geoid), so that at any point not on the geoid, since the time depends on the local gravitational potential, the unit of time differs from the SI second. An analogous situation occurs, of course, with respect to the definition of the unit of time in the reference system fixed at the barycenter of the solar system, based on the recommendation of IAU resolution 5(c) (1976), according to which the terrestrial and barycentric dynamic time scales must differ from one another only by periodic terms.

As regards the units of distance, Japanese researchers (T. Fukushima, M.-K. Fujimoto, H. Kinoshita, and S. Aoki) proposed alternative solutions which reduce to the following:

1) The numerical value of the velocity of light $\tilde{c}_{\text{BO}}$, expressed in units of length and time at infinity, where the gravitational effect of the sun is vanishingly small, is to be regarded as identical to the numerical value $\tilde{c}_{\text{L}}$ expressed in SI units.

2) At infinity the unit of length is to be the SI meter either in the old definition (in proper wavelengths of a definite quantum-mechanical transition) or in the new definition (using the SI second as the unit of proper time with the value of the velocity of light).

Thus, introducing the notation $[c]_{\text{L}}$ and $[c]_{\text{B}}$ for the second in the terrestrial (local) and barycentric reference systems, for the frequency ν of radiation determined by the quantum-mechanical transition between levels of the hyperfine structure of the ground state ${}^2\text{S}_{1/2}$ of the cesium atom ${}^{133}\text{Cs}$ we have correspondingly

$$\nu = 9\,1926\,31\,770\ [c^{-1}]_{\text{L}} = 9\,192\,631\,770/\eta\ [\text{c}^{-1}]_{\text{B}},$$

where $\eta = (1-\beta^2)^{1/2}, \beta = \nu/c$.

Since the velocity c is an invariant,

$$c = \tilde{c}_{\text{L}}\,[\text{M}]_{\text{L}}\,[\text{c}^{-1}]_{\text{L}} = \tilde{c}_{\text{B}}\,[\text{M}]_{\text{B}}\,[\text{c}^{-1}]_{\text{B}},$$

whence

$$\tilde{c}_{\text{L}}\,[\text{M}]_{\text{L}} = \tilde{c}_{\text{B}}\eta\,[\text{M}]_{\text{B}},$$

where $\tilde{c}_{\text{L}}$ and $\tilde{c}_{\text{B}}$ are the numerical values of the velocity of light c in the local and barycentric reference frames, respectively.

Thus in the case of the alternative 1)

$$\tilde{c}_{\text{B}} = \tilde{c}_{\text{L}},$$

whence

$$[\text{M}]_{\text{B}} = \frac{[\text{M}]_{\text{L}}}{\eta},$$

and in the case of the alternative 2)

$$[\text{M}]_{\text{B}} = [\text{M}]_{\text{L}},$$

whence

$$\tilde{c}_{\text{B}} = \frac{\tilde{c}_{\text{L}}}{\eta},$$

where $\tilde{c}_{\text{L}} = 299\,792\,458$ in SI units.

After a detailed analysis of both alternatives Fukushima *et al.* arrived at the conclusion that in order to preserve the numerical values of the constants in the IAU (1976, 1979) system it is desirable to regard the SI units of time and length as barycentric. In this case there is also the advantage that there is one numerical value for the velocity of light c, agreeing with the new definition of the meter in the SI system.

Therefore the IAU (1976, 1979) System of Astronomical Constants is correspondingly altered somewhat:

1. Defining constants:

$$k = 0{,}017\,202\,098\,95\ [\text{A}^{3/2}]/[\text{d}],$$
$$c = 299\,792\,458\ [\text{m}]_{\text{B}}\,[\text{s}^{-1}]_{\text{B}} = 299\,792\,458\,[\text{m}]_{\text{L}}\,[\text{s}^{-1}]_{\text{L}}.$$

2. Basic constants:

$$\tau_A = 499\,004\,782\ [\text{s}]_{\text{B}},$$
$$a_e = 6\,378\,140\,[\text{m}]_{\text{B}},$$
$$\text{GE} = 3.986\,005\cdot 10^{14}\ [\text{m}^3]_{\text{B}}\,[\text{s}^{-2}]_{\text{B}}.$$

3. Derived constants:

$$\text{GS} = 1.327\,124\,385\,769\,386\,5\ \ldots\ \cdot 10^{20}\ [\text{m}^3]_{\text{B}}\,[\text{s}^{-2}]_{\text{B}},$$
$$A = 1.495\,978\,701\,495\,341\,6\ \ldots\ \cdot 10^{11}\ [\text{m}]_{\text{B}}.$$

---

[1] V. K. Abalakin and M. A. Fursenko, Byull. Inst. Teor. Astron. Akad. Nauk SSSR **11**, 131 (1968).

[2] V. K. Abalakin, Astron. Zh. **58**, 465 (1981) [Sov. Astron. **25**, 263 (1981)].

[3] N. I. Idel'son (Soviet Astronomy Yearbook for the year 1942 (1941) (in Russian).

[4] W. Pauli, *Theory of Relativity*, Pergamon Press, New York, 1958 [Russ. transl. of original German 1921 edition, Gostekhizdat, M., L., 1947].

[5] H. Morrith, Vermess., Photogramm., Kulturtehn. 1975. Fachbl. III/IV; Bull. Geod., No. 3 (1981).

[6] T. Lederle, Mitteil. Astron. Ges., Nr. 48 (1980).

[7] T. Fukushima, M.-K. Fujimoto, H. Kinoshita, and S. Aoki, System of Astronomical Constants in the Relativistic Framework, Cel. Mech. (1984).