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EPM — High-Precision Planetary Ephemerides of IAA RAS for Scientific Research and Astronavigation on the Earth and in Space

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Abstract. The last version of the planet part of EPM's ephemerides of IAA RAS (EPM2011) is described briefly. At present EPM ephemerides are the basis for the Russian Astronomical and Nautical Astronomical Yearbooks and are used for scientific research.

Keywords. astrometry, ephemerides, reference systems, relativity, dark matter

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The EPM ephemerides (**E**phemerides of **P**lanets and the **M**oon) of the IAA RAS originated in the 1970's and have been improved since that time. These ephemerides are based upon relativistic equations of motion for celestial bodies and light rays, as well as relativistic time scales. The numerical integration of the equations of motion of the celestial bodies has been performed in the Parameterized Post-Newtonian N-body metric for General Relativity in the TDB time scale. EPM ephemerides are computed in the barycentric coordinate frame of J2000.0 over a 400-year interval (1800–2200) using the program package ERA-7 (ERA: **E**phemeris **R**esearch in **A**stronomy) (Krasinsky, G. A., & Vasilyev, M. V., 1997, Proc. IAU Colloq. 165, 239–244).

For constructing planetary ephemerides using the best modern observations, it is necessary to take into account all influencing factors. The dynamical model of the planetary part of the EPM ephemerides includes mutual perturbations from the major planets, the Sun, the Moon; perturbations from 301 large asteroids and the 21 largest trans-neptunean objects (TNO); perturbations from a modeled massive asteroid ring with a uniform mass distribution; perturbations from a similar massive ring of TNO's in the ecliptic plane with a radius of 43 au; and perturbations due to the solar oblateness.

The EPM2011 ephemerides have been fitted to about 680 000 observations of different types, spanning 1913–2010, from classical meridian observations to modern planetary and spacecraft ranging. The ephemerides of the inner planets are based fully on radiotechnical observations (mostly, measurements of time delays). The ephemerides of the outer planets are mainly based on optical measurements taken since 1913. In addition to optical observations of these planets, positional observations of the satellites of the outer planets are used, as these observations are more precise and practically free from the phase effect, which is difficult to take into account. The reduction of the radar measurements includes all the relevant corrections. These observations have been reduced using relativistic corrections — the time delay of the propagation of radio signals in the gravitational fields of the Sun, Jupiter, Saturn (the Shapiro effect), and the reduction of observations from the coordinate time of the ephemerides to the proper time of the observer. In addition, the radar observations of Mercury, Venus, and Mars are corrected for their topography and for the extra delay of electromagnetic signals in the Earth's

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troposphere and in the solar corona. The main reductions of optical observations of planets involve the correction to the additional phase effect, the corrections for referring the observations to the ICRF reference frame, and the relativistic correction for light bending. For the transition from the time of observations (UTC) to Barycentric Dynamical Time (TDB), the time used in the construction of modern planet ephemerides, it is necessity to convert between Terrestrial Time (TT) and TDB. For the TT–TDB conversion, the differential equation from the paper by Klioner (Klioner, S. A., *et al.*, 2010, Proc. IAU Symp. 261, 112–123) has been used, and TT–TDB was obtained by numerically integrating the EPM.

For improvement of the planetary part of EPM2011, about 270 parameters are determined: orbital elements of the planets and the 18 satellites of the outer planets; the length of the astronomical unit or the value of the solar mass parameter; three angles of orientation with respect to the ICRF frame; parameters of the rotation of Mars and topography of the inner planets; masses of asteroids, the asteroid belt, and TNO's; as well as, some post-model parameters (β, γ, $\dot{G}/G$, $G\dot{M}_\odot/GM_\odot$, $\dot{\pi}_i$, $\dot{a}_i/a_i$, etc.).

EPM2011 has been oriented to the ICRF with an accuracy better than 1 mas by including into the total solution the 213 ICRF-based VLBI measurements of spacecraft taken from 1989–2010 near Venus, Mars, and Saturn (in mas): $\varepsilon_X = -0.000 \pm 0.042$, $\varepsilon_Y = -0.025 \pm 0.048$, $\varepsilon_Z = 0.004 \pm 0.028$. The present maximum errors of the coordinates of the Earth orbit determined from a comparison of the EPM2011 heliocentric X, Y, Z coordinates, velocities, and distances with those of DE424 in the 1950–2050 time interval are less than 250 m (coordinates), 0.05 mm s^{-1} (velocities), 6 m (distances).

At present EPM ephemerides are used for astronavigation on the Earth and space: they are the basis for the Russian Astronomical and Nautical Astronomical Yearbooks since 2006, and are used in the GLONASS and LUNA-RESOURCE programs and for various other investigations.

The masses of 21 largest asteroids have been estimated directly from spacecraft ranging, and masses of others in the group of 301 asteroids have been obtained from their known diameters and the estimated densities for the three taxonomic typess (C, S, M). From the estimates of the masses of all asteroids and the asteroid ring we obtain the value of the total mass of the asteroid main belt: $M_{\rm belt} = (12.3 \pm 2.1) \cdot 10^{-10} M_\odot$ ($\approx 3\, M_{\rm Ceres}$). From the mass estimate of the TNO ring and the known masses of the 21 largest TNO and Pluto we obtain the total mass of all TNO: $M_{\rm TNO} = 790 \cdot 10^{-10} M_\odot$ ($\approx 164\, M_{\rm Ceres}$ or $2\, M_{\rm Moon}$). These estimates illuminate the dynamics of the Solar System now and at its formation (Pitjeva, E. V., Proc. Inter. Conf. "Asteroid-Comet Hazard – 2009", 2010, 237-241).

New estimations of PPN parameters have also been obtained: β–1 $= -0.00002 \pm 0.00003$, γ–1 $= +0.00004 \pm 0.00006$. The good correspondence of the planetary motions and the propagation of light to the predictions of General Relativity narrows significantly the range of possibilities for alternative theories of gravitation (Pitjeva, E. V., Proc. IAU Symp. 261, 2010, 170-178).

It has been found that the solar mass parameter $GM_\odot$ decreases at a rate of $G\dot{M}_\odot/GM_\odot = (-5.04 \pm 4.14) \cdot 10^{-14}$ per year (3σ). The annual change of the gravitation constant G must fall within the interval $-4.2 \cdot 10^{-14} < \dot{G}/G < +7.5 \cdot 10^{-14}$ with a 95% probability (Pitjeva, E. V. & Pitjev, N. P., 2012, Solar System Research, 46, 78-87).

Using estimates of the additional perihelion advances obtained from observation for different planets, it has been found that the density of dark matter $\rho_{\rm dm}$ must be less than $1.1 \cdot 10^{-20}$ g cm^{-3} at the distance of Saturn's orbit, and the mass of dark matter inside Saturn's orbit must be less than $1.7 \cdot 10^{-10} M_\odot$, even if it concentrated toward the center (Pitjev, N. P. & Pitjeva, E. V., 2013, Astronomy Letters, 2, in press).