Estimates of the changes of the gravitation constant G and the $GM_{\odot}$ based on updated EPM2019 ephemeris

Pitjeva[1] E.V., Pitjev[2] N.P., D. A. Pavlov[1]
[1]Institute of Applied Astronomy RAS, e-mail: evp@ipa.nw.ru
[2]St. Petersburg State University, e-mail: ai@astro.spbu.ru

Journees-2019, 7-9 October 2019, Paris

Is the gravitational constant G constant?

There is here great interest in the question of the constancy of the gravitational constant G, which is an important fundamental physical quantity. On the one hand, Einstein's theory of general relativity says that G is the same everywhere. However, new theories of gravity (String Theory, etc.) say: the gravitational “constant” is rather a derivative parameter that can change over space time (see, for example, the reviews of Uzan 2003, 2011 and Chiba 2011).

Consistency G is an empirical question that can be investigated using astrophysical experiments. The strongest restrictions today are associated with the dynamics of the solar system.

The Lunar Ranging experiment (Smullin & Fiocco 1962; Murphy 2013) gives $\dot{G}/G = (7.1 \pm 7.6) \times 10^{-14}$ years $^{-1}$ over the past few decades (Hofmann & Muller 2018).

From the Messenger spacecraft (Genova et al. 2018) and the ephemeris of Mercury, it was found that $|\dot{G}/G| < 4 \times 10^{-14}$ year $^{-1}$ for the last seven years.

Influence change of $GM_\odot$ on planetary motions

Using the laws of celestial mechanics and planetary ephemeris in the solar system, one can find how the product $GM_\odot$ - the heliocentric gravitational constant of the Sun changes, since the equations of motion include the products GM_i, of which $GM_\odot$ is largest and important (Pitjev,Pitjeva 2012).

A change of $GM_\odot$ preserves the area integral, but leads to a change in the semiaxes a_i, periods of T_i, and a shift in longitude L_i of planes, and the shift in longitude increases in proportion to the square of the time (Pitjev, Pitjeva 2012). The increase in the time interval and high-precision observations make it possible to refine the value $d(GM_\odot)/dt$.

In our work, a new version of the planetary ephemeris EPM2019 was used to find the $GM_\odot$ change.

Increase in the number of used observations

Ephemerides	**EPM2010**		**EPM2019**	
type	**Radio**	**Optical**	**Radio**	**Optical**
interval	**1961-2009**	**1913-2009**	**1961-2017**	**1913-2013**
Number of n.p. /obser.	**577763 ob.**	**57768 ob.**	**61866 n.p.**	**72929 ob.**

The new radar observations: VEX 2006-2012, MEX(2009-2015), Odyssey(2002-2017), MRO(2006 -2017), Cassini (2004-2014), Messenger (2011-2015), Juno (2016-2017).

The new optical observations obtained at the Observatories: TMO, Flagstaff, Pulkovo, Lowell, Pico dos Dias.

The motion of the Sun, the planets (including Pluto), and the Moon (as point-masses) obeys the Einstein-Infeld-Homann relativistic equations, with additional perturbations from: solar oblateness, 301 largest asteroids and 30 largest trans-neptunian objects (TNO), as well as two annuli: the asteroid belt, and the Kuiper belt. For improvement of the planetary part of EPM2019, about 270 parameters were determined.

Evolution of Ephemerides 1987-2019

Ephemerides	Discription
EPM87	• Mutual perturbations from the major planets, the Sun, the Moon and 5 most massive asteroids; • the relativistic perturbations
EPM98	• perturbations from the other 301 asteroids chosen due to their strong perturbations upon Mars and the Earth.
EPM2000	• perturbations due to the solar oblateness J_2; • perturbation from a massive one-dimensional ring of asteroids
EPM2008	• perturbations from the 21 largest TNO
EPM2011	• perturbation from ring of TNO in the ecliptic plane with the R=43 au
EPM13/EPM2014	• perturbation from the massive two-dimensional asteroid ring (R_1= 2.06 au, R_2 = 3.27 au); • perturbations from the 30 largest TNO
EPM2015	• the new version of program package ERA (Ephemeris Research in Astronomy), ERA-8, based jg the RacketFormain-specific language SLON tailored for astronomical tasks. • Updated lunar model based on DE430.
EPM2019	• perturbations from the massive two-dimensional discrete rotatin asteroids and Kuiper rings (2018); • perturbations from Jupiter’s Trojans with estimated dynamical masses.

The determined value of the GM$_\odot$ change

The following value of the GM$_\odot$ change was obtained:

$$(G\dot{M}_\odot)/GM_\odot = (-10.2 \pm 1.4) \cdot 10^{-14}\ \mathrm{yr}^{-1}\ (3\sigma)$$

This value includes a change in the mass of the Sun M$_\odot$ and a possible change in the gravitational constant G. Therefore, to obtain a change of G, the secular change in the mass of the Sun M$_\odot$ should be taken into account.

$$(G\dot{M}_\odot)/GM_\odot = \dot{M}_\odot/M_\odot + \dot{G}/G\ .$$

$$-11.6 \cdot 10^{-14} < \dot{M}_\odot/M_\odot + \dot{G}/G < -8.8 \cdot 10^{-14}\ \mathrm{yr}^{-1}\quad (3\sigma)$$

The change in the mass of the Sun $M_\odot$

The decrease of the solar mass:

a)Thermonuclear reactions take place on the Sun and a decrease in the mass of the Sun through the total radiation flux is:

$$(\dot{M}_\odot / M_\odot)_{rad} = -6.789 \cdot 10^{-14} \ \text{yr}^{-1} .$$

b) Fluctuations of this value averaged over the duration of the solar cycle are small ~ 0.1- 0.2%, hence

$$-6.830 \cdot 10^{-14} < (\dot{M}_\odot / M_\odot)_{rad} < -6.748 \cdot 10^{-14} \ \text{yr}^{-1} . \qquad (3\sigma)$$

The decrease of the solar mass due to the solar wind

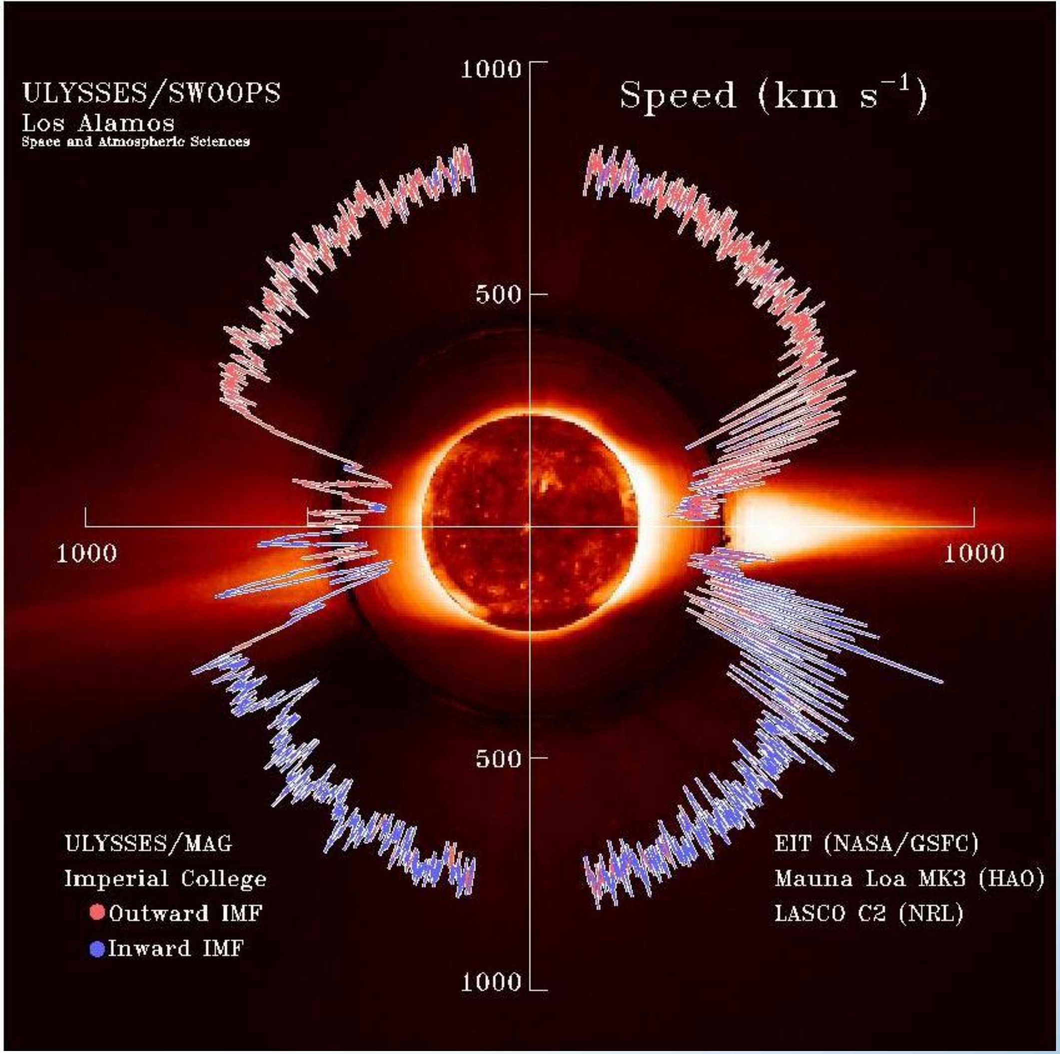
c) The decrease in the mass of the Sun due to the solar wind was estimated according to the Ulysses spacecraft.

Data cover a time interval of more than one solar cycle (from 11.18.1990 to 06.30.2009), capturing parts 22 and 23 of the cycle; and it is important that the trajectory of the apparatus was almost polar relative to the equator of the Sun.

Solar wind flux data were often measured over time and are provided every hour for the entire measurement interval. They were used during processing and to obtain the annual flow of the carried-away mass averaged over the solar cycle: The decrease of the solar mass due to the solar wind

$$\left(\dot{M}_\odot/M_\odot\right)_{\mathrm{wind}} = (-4.8 \pm 2.4) \bullet 10^{-14}\ \mathrm{yr}^{-1} \qquad (3\sigma)$$

Solar wind, Ulysses



https://ufa.esac.esa.int/ufa/#data

The increase of the solar mass

c) Estimation of the increase in the mass of the Sun due to the falling matter, $\dot{M}_{\odot \mathrm{fall}}/M_{\odot} < +3.2 \cdot 10^{-14}$,
as was immediately noted in the work (Piteva, Pitev 2012), it was an estimate from above and greatly overestimated.

Observational data and calculations show that dust particles cannot approach the Sun due to solar wind pressure and solar radiation heating (Klacka et al., 2012, Solar wind and motion of dust grains. Mon. Not . R. Astron. Soc.)

Also, current space observations confirm the rarity of the close passage of comets to the Sun. The very rare fast passage of comet nuclei through the corona of the Sun, as a rule, leads to the loss of only a part of the material of the comet nuclei, and the size of the nuclei is significantly smaller than those taken in our article (Pityeva, Pitiev 2012).

The new mass estimate of the falling material

Our new estimate from above of the mass of the falling material on the Sun is reduced by about three times:

$$\dot{M}_{\odot\,\mathrm{fall}}/M_\odot < +1.0 \cdot 10^{-14}\ \mathrm{yr}^{-1} ,$$

and it probably overstated by an order of magnitude or more.

The upper and lower boundaries of the change of the mass of the Sun within 3σ (σ is the standard error) taking into account radiation, the solar wind, and asteroid fall will be:

$$-14.0 \cdot 10^{-14} < (\dot{M}_\odot/M_\odot)_{\mathrm{rad+wind+fall}} < -8.1 \cdot 10^{-14}\ \mathrm{yr}^{-1}. \quad (3\sigma)$$

We have inequality

$$-11.6 \cdot 10^{-14} < \dot{M}_\odot/M_\odot + \dot{G}/G < -8.8 \cdot 10^{-14}\ \mathrm{yr}^{-1} \quad (3\sigma)$$

Estimation of the g change

From the last two inequalities, we obtain restrictions on the change in the gravitational constant G. From the last two inequalities, we obtain restrictions on the change in the gravitational constant **G** :

$$-3.5 \bullet 10^{-14} < \dot{G}/G < +5.2 \bullet 10^{-14} \quad . \qquad (3\sigma)$$

Our result using the new version of planetary ephemeris EPM2019 made the restriction on the change in the gravitational constant G narrower compared to the previous result with EPM2010.

$$-7.0 \bullet 10^{-14} < \dot{G}/G < +7.8 \bullet 10^{-14} \quad , \qquad (2\sigma)$$

where the possible interval for the value $\dot{G}/G$ was given for 2σ.

The results obtained are consistent with the General Theory of Relativity.

Comparison of estimates of G change

Year	Autor	$\dot{G}/G$ yr $^{-1}$	Remark
2012	Pitjeva, Pitjev	$-4.2\cdot10^{-14} < .. < +7.5\cdot10^{-14}$	Dynamics of the solar planets
2015	Fienga, Laskar et al.	$< 8\cdot10^{-14}$	Dynamics of the solar planets
2017	Bonanno, Frohlich	$(1.25 \pm 0.30)\cdot10^{-13}$	Helioseismology
2018	Hofmann, Muller	$(7.1 \pm 7.6)\cdot10^{-14}$	Lunar laser ranging (LLR)
2018	Genova, Mazarico et al.	$< 4\cdot10^{-14}$	Mercury's ephemeris, Messenger mission
2019	Bellinger, Christensen-Dalsgaard	$(2.1 \pm 2.9)\cdot10^{-12}$	Asteroseismology
2019	**Pitjeva, Pitjev**	$-3.5\cdot10^{-14} < .. < +5.2\cdot10^{-14}$	Dynamics of the solar planets

The result obtained is consistent with the latest estimates obtained by american astronomers for observational data of the Messenger spacecraft and the refined ephemeris of Mercury (Genova, A., Mazarico, E., Goossens, S., et al. 2018, Nature Comm., 9, 289)

СПбГУ

Thank you for your attention !