Estimates of the change rate of solar mass and gravitational constant based on the dynamics of the Solar System

E. V. Pitjeva¹, N. P. Pitjev¹,², D. A. Pavlov¹,³, and C. C. Turygin¹,²

¹ Institute of Applied Astronomy of Russian Academy of Sciences (IAA RAS), Kutuzov Quay 10, 191187 St. Petersburg, Russia
e-mail: evp@iaaras.ru
² St.Petersburg State University, Universitetski pr. 28, 198504 Petrodvoretz, Russia
e-mail: ai@astro.spbu.ru
³ St. Petersburg Electrotechnical University, ul. Professora Popova 5, 197376 St. Petersburg, Russia
e-mail: dapavlov@etu.ru

Received 11 November 2020 / Accepted 3 February 2021

ABSTRACT

The estimate of the change rate of the solar gravitational parameter \(d(GM_\odot)/dt\) is obtained from processing modern positional observations of planets and spacecraft. Observations were processed and parameters were determined basing on the numerical planetary ephemeris EPM2019. The obtained annual decrease in solar mass \(M_\odot\) accounts for the loss through radiation \(M_{\text{rad}}\) through the outgoing solar wind \(M_{\text{wind}}\), and for the material falling on the Sun \(M_{\text{fall}}\). The estimated relative value is within \(-13.4 \times 10^{-14} < (M_{\odot}/M_\odot)_{\text{rad,wind,fall}} < -8.7 \times 10^{-14}\) per year. The following range for the change rate of the gravitational constant \(G\) was obtained: \(-2.9 \times 10^{-14} < G/\dot{G} < +4.6 \times 10^{-14}\) per year (3\(\sigma\)). The new result reduces the interval for the change in \(G\) and narrows the limits of possible deviations for alternative gravitational theories from general relativity.

Key words. methods: numerical – celestial mechanics – techniques: radar astronomy – Sun: fundamental parameters – planets and satellites: fundamental parameters – solar wind

1. Introduction

The source of the Sun’s energy is thermonuclear fusion in its interior, which means that the mass of the Sun must be changing. The generated energy \(\Delta E_\odot\) obeys Einstein’s formula \(E = mc^2\) and thus gives the corresponding decrease in solar mass \(\Delta M_\odot\). The other physical effect that causes the decrease in solar mass was detected much later with the discovery of the continuous flow of plasma out into the interplanetary space, called solar wind (Parker 1958).

Coronal ejections add material to the solar wind. This is amplified during periods of active Sun. Although the combined mass loss of the Sun due to solar radiation and solar wind is millions of tons per second, the relative change is very small. First experimental results on the change in the product \(GM_\odot\) (the gravitational parameter of the Sun) were obtained in 2012 (Pitjeva & Pitjev 2012) from the motions of the planets in the Solar System.

From the equations of motion of celestial mechanics it is impossible to determine a direct change in mass of the central body \(\Delta M_\odot\), and it is only possible to determine the change products of \(\Delta(GM_\odot)\) because the equations include products of mass by the gravitational constant \(G\). The important problem of constancy or variability of \(G\) arises here.

The question of the possible variability of \(G\), an important fundamental physical quantity, has been discussed for a long time. In the general theory of relativity (GRT), \(G\) is a main parameter and has a constant value. However, some works have considered a variable \(G\): Dirac (1937, 1938) and Milne (1937). In versions of the modified theory of gravity, as well as in alternative theories of gravity, \(G\) can change and is in fact a parameter (see, e.g., reviews of Uzan 2003, 2011 and Chiba (2011) about how \(GM_\odot\) affects the motion of the planets). The alternative theories of gravity include scalar-tensor theories (Fujii & Maeda 2003), quantum-gravitational theories (Bonanno et al. 2004, Smolin 2015), models of superstring theory, and cosmology with the variable \(G\) (Hanmieli et al. 2020). It is important to verify the constancy or variability of \(G\) for cosmological theories and for possible modifications in the theory of gravity. Data from various fields of astrophysics can be useful for this purpose.

Local (in time and space) constraints were obtained from data for double pulsars (Zhu et al. 2019), for exoplanets (Masuda & Suto 2016), and on primary nucleosynthesis (Alvey et al. 2020). The range of opportunities for the experimental evaluation of theories gradually expands, and the answer to this question is currently being sought through physical and astronomical experiments. The strongest restrictions on variations of the gravitational constant \(G\) are obtained today from the dynamics of the Solar System. High-precision theories of motion have been designed and built for the celestial bodies of the Solar System: DE (Development ephemeris, Folker et al. 2014), EPM (Ephemerides of planets and the Moon, Pitjeva et al. 2019), and INPOP (Intégrateur Numérique Planétaire de l’Observatoire de Paris, Viswanathan et al. 2018). These ephemerides are publicly available¹,²,³.

All this opened up an opportunity to consider the Solar System as a huge laboratory for testing a number of important principles of fundamental physics for gravitating bodies. In particular, finding a change for the gravitational parameter of the Sun \(\Delta(GM_\odot)\) allows us to analyze possible bounds for \(\Delta M_\odot\) and \(\Delta G\); the latter is important for testing the constancy or variability of the gravitational constant.

¹ https://ssd.jpl.nasa.gov/?planet_eph_export
² http://iaaras.ru/dept/ephemeris/epm
³ https://www.imcce.fr/inpop

Article published by EDP Sciences
2. Effects of change in $GM_⊙$ on planetary motion

To a certain extent, the masses of all bodies in the Solar System can change (through the fall of asteroids, loss of gas from the atmosphere, etc.), but the Sun is currently the only body for which we can detect the effect of mass loss on gravity bodies because the mass of the Sun is many orders of magnitude greater than the masses of planets and other bodies. With the achieved accuracy of modern planetary ephemerides, the change rate in $GM_⊙$ can be detected by a small change in the rate of the orbital movement of the bodies.

Changes in the masses of other bodies, including Jupiter, affect the planetary motion much less strongly. The current accuracy of observations and planetary theories means that these changes still cannot be detected.

With the assumed slow isotropic mass loss of $M_⊙$ associated with solar radiation and the solar wind, the angular momentums of the planets are preserved, but their semimajor axes $a_i$ change. At the same time, eccentricity, and position of the pericenter are preserved. Each orbit gradually transforms, remaining similar to itself, and resembles a spiral.

Direct search for a resizing of orbits due to the time evolution of the value of $GM$ for the central body (as was noted by Pitjeva & Pitjev 2012) is ineffective because over a time interval of several tens or hundreds of years, the effect is too small. It is difficult to overcome the complexity in practical measurements of very small effects against the background of existing objective errors for the parameters of planetary orbits, even for high-precision observations. It is important that along with the change in the semimajor axes $a_i$, the orbital periods $T_i$ change, however. This key point opens up the possibility of detecting the effect of a small change in $GM_⊙$, as there is a shift in the position of bodies in longitude $Δλ_i$, and the longitudinal displacement increases with each revolution of the planet around the Sun. The change rate of the movement leads to a shift in the position of the body throughout the orbit in proportion to the square of the time interval $(Δt)^2$. Using long-range observations allows us to find the change over time $d(GM_⊙)/dt$.

3. Planetary ephemeris EPM2019 and observations

The value of $d(GM_⊙)/dt$ was determined as part of a least-squares fitting of a large number of parameters to a large number of observations, which is normally done to build planetary ephemerides, in this case, the ephemerides of the planets and the Moon (EPM). These ephemerides were created in the 1970s in support of Russian space flight missions; later, their development continued in the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS). The EPM contain coordinates and velocities of the Sun, the Moon, the eight major planets, Pluto, the three largest asteroids (Ceres, Pallas, and Vesta) and four transneptunian objects (TNOs: Eris, Haumea, Makemake, and Sedna), as well as the lunar libration and the difference between the Terrestrial time and the Barycentric dynamical time (TT–TDB). The modern EPM cover more than 400 yr (1787–2214) except for the “long” ephemeris EPM2017H, which spans an interval of more than 13 100 yr. The dynamical model of the EPM is based on the parameterized post-Newtonian N-body metric for general relativity in the barycentric coordinate system (BCRS) and the TDB timescale. The motion of the Sun, the planets (including Pluto), and the Moon (as point-masses) obeys the Einstein-Infeld-Hoffmann relativistic equations.

Standard procedures were carried out to determine corrections to the parameters values using the iterative least-squares method fed with the entire set of observations. The method was repeatedly applied until the corrections to the parameters became smaller than their error estimates. Several iterations were usually required. All observations were weighted according to their accuracy. The parameters depend on the observations used. For early radar observations of planetary surfaces, it is necessary to know the parameters of the planet surface topography; for the three Martian landers (Viking 1 and 2, and Pathfinder), 13 parameters of the rotation of Mars and three parameters of the coordinates for each lander need to be determined. To process the ranging observations of planetary orbiters, factors of the solar plasma correction were determined for each conjunction of the planet with the Sun (21 parameters). The most important parameters are the orbital elements of the nine planets (including Pluto) and 18 main satellites of the outer planets (162 parameters), however. A total of 264 parameters were determined for all observations.

The modern EPM is significantly more advanced than the EPM2010, both for an improved dynamical model and for a wider range of high-precision observations. For the detection of change in solar mass, the accuracy of the mean planetary longitudes is most important because the semimajor axes of the planets and the periods of the orbital motion are sensitive to the change in solar mass (see Sect. 2). Compared to EPM2010, the errors of the mean longitudes in EPM2017 have decreased for almost all planets, except for Neptune, for which only one three-dimensional point was obtained from the data of the Voyager 2 spacecraft. The errors in mean longitudes of Mercury and Mars have decreased by more than an order of magnitude based on observations of the Martian orbiters and the MESSENGER (Mercury Surface, Space Environment, Geochemistry, and Ranging) orbiter and taking the Lense-Thirring relativistic effect into account (Pitjeva & Pitjev 2018a, Table 3).

We determined the change in solar mass simultaneously with all parameters, except for the masses of asteroids, which correlate with each other and would affect the uncertainty of the change in solar mass. The asteroid masses were determined independently from $d(GM_⊙)/dt$, but together with the other parameters of the planetary ephemeris.

The time interval of the observations exceeds 100 yr (1913–2017) and includes optical observations and normal points of radio-technical observations (see Table 1). The number of high-precision radio observations on which the EPM are based increases constantly. When EPM2010 was released, about 800 000 observations were collected. More than 850 000 observations are used in the current version of the EPM2019 planetary theory. However, individual spacecraft measurements are not used in ephemerides, only 51 858 normal points. Normal points were made from raw observations by William Folkner (NASA JPL); each normal point represents the observations of one spacecraft revolution around the planet (these observations correlate with each other). Table 1 shows the number of normal points for ranging data and the number of observations for optical data. For the ephemerides of the inner planets, only high-precision radio-technical measurements are currently used, which cover a time interval of more than half a century. Optical observations are inferior in accuracy by several orders of magnitude, and were not used for these planets.

The most accurate are radio ranging measurements of planetary orbiters: Mercury (MESSENGER 2011–2015, 0.7 m), Venus (Venus Express 2006–2012, 3 m), Mars (Mars Express 2009–2015, 1.5 m; Odyssey 2002–2017, 1 m; Mars Reconnaissance Orbiter 2006–2017, 1 m), Saturn (Cassini 2004–2014, 20 m), and Jupiter (Junoc 2016–2017, 11 m). The values in parentheses are the
Table 1. Observations used to estimate the parameters.

| Type       | EPM2010          | EPM2019          |
|------------|------------------|------------------|
|            | Radio normal points | Optics observations | Radio normal points | Optics observations |
| Interval   | 1961–2009         | 1913–2009        |
| Number     | 7229              | 57788            |
| Number     | 1961–2017         | 1913–2013        |
| Number     | 51858             | 72849            |

root-mean-square postfit residuals (see Pitjeva & Pitjev 2018b,a, 2019 for details).

Recent optical observations of good (<1") accuracy were obtained from observatories: TMO (USA), Flagstaff (USA), Lowell (USA), and Pico dos Dias (Brazil). The dynamical model has become more accurate than the model in EPM2010. The EPM2010 model included mutual perturbations from the major planets, the Sun, the Moon, and 301 asteroids chosen because they strongly perturbed Mars and Earth; it included the main relativistic perturbations, perturbations due to the solar oblateness $J_2$, and perturbations from the 21 largest TNOs. The EPM2019 model in addition includes perturbations from the other nine largest TNOs, perturbations from discrete massive two-dimensional rotational rings of main-belt asteroids and TNO rings, and perturbations of the next order of smallness, which also affect the motion of the planets. It also includes the relativistic Lense-Thirring effect and the Jupiter trojans (Pitjeva & Pitjev 2018b,a, 2019).

Since EPM2017, the EPM are being built using the ERA-8 software (Pavlov & Skripnichenko 2016). Recent improvements to this software relevant to planetary dynamics are the inclusion of two-dimensional discrete rotating rings accounting for the Kuiper belt and for the small asteroids in the main belt (Pitjeva & Pitjev 2018b,a), the relativistic Lense-Thirring effect, and two numerous groups of Jupiter trojans (Pitjeva & Pitjev 2019). The Lense-Thirring effect is especially important for the determination of the time-varying value of $GM_\odot$ because it allows us to build a much more correct orbit of Mercury, which is fit to the ranging observations of the MESSENGER spacecraft. An important technical achievement was also made with the new multistep integrator (Aksim & Pavlov 2020), which is capable of handling delay differential equations in a manner that does not decrease the performance. Because the planets and the Moon are integrated together and because the lunar equations contain delay (Pavlov et al. 2016), the new integrator has allowed to build the ephemeris twice as fast.

The following value was estimated for the change rate of $GM_\odot$:

$$\frac{d(GM_\odot)}{dt} = (-10.2 \pm 1.4) \times 10^{-14} \text{ per year (3σ).} \quad (1)$$

This is the value for the annual change in the solar gravitational parameter ($GM_\odot$) and includes the annual change in solar mass $M_\odot$ and a possible annual change in the gravitational constant $G$. We note the following relation for $d(GM_\odot)/dt$:

$$\frac{d(GM_\odot)}{dt} = \frac{\dot{G}}{G} + \frac{M_\odot}{M_\odot}, \quad (2)$$

hence

$$-11.6 \times 10^{-14} < \frac{\dot{G}}{G} + \frac{M_\odot}{M_\odot} < -8.8 \times 10^{-14} \text{ per year, (3σ)} \quad (3)$$

4. Change rate in solar mass

The change rate in solar mass ($\dot{M}_\odot$) has several components. First of all, the solar mass decreases as a result of thermonuclear fusion with the release of energy $M_\odot{\rm{rad}}$, which provides continuous powerful radiation from the Sun. Second, the plasma of the solar corona has a very high temperature and is emitted into interplanetary space in the form of an accelerated solar wind $M_\odot{\rm{wind}}$ which continuously carries matter away, along with charged wind particles and solar material. Third, a certain amount of dust particles falls onto the Sun due to the Poynting-Robertson effect; also certain number of comets, asteroids, and meteoroids fall onto the Sun due to the evolution of their orbits. We denote the change rate due the falling material ($M_\odot{\rm{fall}}$). Considering these components, the total change rate in solar mass is

$$M_\odot{\dot{}} = (M_\odot{\dot{}})_{{\rm{rad}}} + (M_\odot{\dot{}})_{{\rm{wind}}} + (M_\odot{\dot{}})_{{\rm{fall}}}. \quad (4)$$

4.1. Solar radiation

The value of the nominal solar radiation per second, covering the full range of electromagnetic waves, and adopted by the International Astronomical Union in 2015, is equal to

$$L_0 = 3.828 \times 10^{26} \text{ W} = 3.828 \times 10^{33} \text{ erg s}^{-1} \quad (5)$$

(Resolution B3, International Astronomical Union, 2015). This radiation energy corresponds to solar mass loss of

$$\frac{\dot{M}_\odot}{M_\odot} = -6.760 \times 10^{-14} \text{ per year}. \quad (6)$$

There are small variations in the solar flux around this value. They are related to the 11-year solar cycle with a maximum deviation of about 0.1%, as well as to changes of about 0.2%, related to the 27-day period of the solar rotation around its axis (Fröhlich & Lean 2004). These changes involve the ultraviolet, visible, and infrared regions of the spectrum, with large changes at shorter wavelengths. Variations in solar radiation are clearly traced by solar magnetism. The active regions alter the local radiation, and the contrasts depending on the wavelength relative to the quiet Sun determine the variability of the flow. The solar emissivity also reacts to the subsurface convection and hot plasma flows in the Sun. On the shortest timescales, the total radiation shows five-minute fluctuations with an amplitude of $\approx 0.003\%$ and can increase to 0.015% during the largest solar flares.

In general, fluctuations in solar flux during the solar cycle are small and amount to $\sim 0.1\% - 0.2\%$ (Wu et al. 2018; Tagirov et al. 2019). Based on the maximum estimate for fluctuations, the average annual loss of solar mass $\dot{M}_\odot{\rm{rad}}$ therefore is within the range of $-6.8 \times 10^{-14} < (M_\odot{\dot{}})_{{\rm{rad}}} < -6.719 \times 10^{-14} \text{ per year (3σ)}$.

The possible range for the deviation from the nominal average value $\dot{M}_\odot{\rm{rad}}$ due to fluctuations associated with various solar activities is insignificant compared with the fluctuations for the mass that is carried away per unit time by the solar wind $\dot{M}_\odot{\rm{wind}}$.

4.2. Solar wind

The solar wind is a stream of charged particles coming out of the base of the solar corona. Material is added to the base of the solar corona. The stationary part of the flow consists of fast (from 600 km s$^{-1}$ to 800 km s$^{-1}$) and slow (up to 450–500 km s$^{-1}$) wind (Belcher & Davis Jr 1971). These components can vary with time and fluctuate in density. The fast solar wind occurs in coronal holes.
The origins of the slow solar wind are not established clearly yet and are still discussed (Antonucci et al. 2005; Abbo et al. 2016). They have been associated with active areas on the Sun. Generally, the solar wind is a large-scale plasma outflow, and its mass is almost entirely composed of protons and alpha particles. The electron mass contributes approximately three orders of magnitude less. The proportion of other elements is insignificant. Coronal emissions significantly affect fluctuations in the solar wind density. The number and intensity of the emissions depend on solar activity, the number of sunspots, and on the solar cycle phase. The emissions of magnetized plasma are usually closely related to solar flares (Compagno et al. 2017). The main share of the emissions falls on latitudes $-60^\circ \leq b \leq 60^\circ$. The solar mass loss due to coronal mass ejections is an order of magnitude lower than that of the solar wind (Mishra et al. 2019), however.

Additional information about the properties of the solar wind has begun to be obtained through the Parker Solar Probe spacecraft (PSP) made by NASA. It operates in the vicinity of the Sun and gradually moves to a trajectory close to the Sun (Halekas et al. 2020; Chen et al. 2020; Rouillard et al. 2020).

During periods of high solar activity, slow winds are observed at all latitudes. At low solar activity the latitudinal structure is bimodal: the slow wind is concentrated in near-equatorial zones, and the fast wind in near-polar zones.

To estimate the mass that is carried away with the solar wind, averaged over the solar cycle, we used data from the Ulysses spacecraft (NASA)\(^4\). Ulysses operated from 1990 to 2008, and the data cover the entire solar activity cycle 23, the final half of solar cycle 22, and the beginning of solar cycle 24. It is important that the trajectory of the spacecraft was almost perpendicular to the solar equator, while perihelion (1.35 AU) and aphelion (5.4 AU) were almost exactly in the plane of the ecliptic. The SWOOPS instrument (Solar Wind Observations Over the Poles of the Sun) measured the characteristics and densities of ion and electron fluxes. From 1990 to 2008, the device made about 600,000 measurements every 15 min. The temperature, density, and velocity of protons and alpha particles data was registered. When we processed the data, we used measurements averaged for each hour of spacecraft work.

The Ulysses data clearly show the latitudinal distribution of the density and velocity, correlated with the solar magnetic structure. Depending on the phase of the solar cycle, the fast and slow winds are more noticeable or fainter. When we found a stream of particles at the spacecraft position, it was considered the same at this time for the entire latitude related to the equator of the Sun. The results were summarized for all latitudes during the entire operation of the Ulysses spacecraft for about 18 yr.

The mass carried away by the solar wind was estimated from the recorded proton and alpha particle flux (SWOOPS). The plasma of the solar wind still contains a stream of electrons, but the mass lost through electrons is more than three orders of magnitude lower than the mass lost through high-mass particles. The fluctuations for the flow of protons and alpha particles are much larger than the mass of the electron flux.

The registration interval of particles by Ulysses began in solar cycle 22 and ended in cycle 24. It significantly exceeded the average period of the solar cycle. To obtain the average annual mass loss due to the solar wind and take the variability during the solar cycle into account, it was averaged using the entire operating interval of the spacecraft. The average period for changes in solar activity was taken to be $T = 11.2$ yr. The average annual mass loss due to the solar wind is

$$
\left( \frac{M_o}{M_o} \right)_{\text{wind}} = (-4.8 \pm 1.8) \times 10^{-14} \text{ yr}^{-1} (3\sigma).
$$

or

$$
-6.6 \times 10^{-14} < \left( \frac{M_o}{M_o} \right)_{\text{wind}} < -3.0 \times 10^{-14} \text{ yr}^{-1} (3\sigma).
$$

An estimate of the mass carried away by the solar wind for a year was found by processing data from the Ulysses spacecraft over the entire 18-yr operation of the Ulysses. Averaging was carried out at each 11.2-yr interval of the solar activity period with a shift of one year from 1990 to 1997 to cover the entire observation interval up to 2008 in 11-yr cycles. The value $\pm 1.8 \times 10^{-14}$ corresponds to the random error found from variations in the average annual solar mass loss due to the solar wind. About 67% of the mass was carried away with the fast wind, and about 33% with the slow wind.

### 4.3. Estimate of the mass falling onto the Sun

The fall of small comets onto the Sun was recorded by spacecraft observing the Sun and the solar corona. Interplanetary dust, meteor matter and asteroids should also be considered part of a possible falling mass. In this case, we can only talk about an approximate estimate because there are not enough observational and experimental data. Results of the PSP spacecraft can improve the situation.

#### 4.3.1. Dust of the interplanetary medium

The dust environment in the Solar System is found from Mercury to the Kuiper belt and might be present in the Oort cloud. It is known from spacecraft observations that it also includes interstellar dust particles passing through our Solar System (Grün et al. 1993; Baguhl et al. 1996; Altobelli et al. 2006). The proportion of the interstellar component is small, however, and is three orders of magnitude lower than the density of interplanetary dust belonging to the Solar System.

The interplanetary dust cloud is strongly concentrated toward the ecliptic plane, and the dust particles spend several thousand years in it, but the interplanetary dust complex in the Solar System is constantly replenished with dust lost by comets and asteroids. Dust particles of the interplanetary medium interact with photons of solar radiation, lose angular momentum under the action of the Poynting-Robertson effect, and gradually approach the Sun in a spiral (Burns et al. 1979). They are also exposed to solar pressure, thermal heating, and sublimation, and when faced with the flow of the solar wind, the dust experiences additional outward-directed pressure (Klačka et al. 2012; Klačka 2014). The lifetime of dust particles in the densest interplanetary environment extending from the main asteroid belt toward the Sun is estimated to be $\sim 10^2$ yr. There is constant exchange due to emission by comets and small fractions formed during asteroid collisions.

A population of very small, nanometer-sized dust particles is carried away by the solar wind (Juhász & Horányi 2013). According to the PSP spacecraft, a large proportion of dust particles in the vicinity of the Sun acquires hyperbolic velocities and is ejected from the Solar System (Szalay et al. 2020).

Thermal sublimation of dust particles predicts a dust-free zone $\sim 4–5 R_\odot$. The results of the PSP indicate the existence of a radiation mechanism of dust destruction (Hoang et al. 2020), which breaks large grains into very small particles. They are in turn destroyed by the bombardment of protons from the solar wind. As a result, the dust-free zone in the immediate vicinity of the Sun is likely $\sim 8R_\odot$.\(^4\)

\[^4\]http://ufa.esac.esa.int/ufa/#data
The total mass of dust in the inner Solar System, including the main belt, is low and is estimated to have a mass of about one asteroid with a diameter of 20 to 30 km. Dust particles drift and dust renewal takes place over several thousand years. If all the dust moving toward the Sun were to reach its surface, then the mass of dust falling onto the Sun due to the Poynting-Robertson effect would be about or lower than $10^{-17} M_\odot$ per year. Solar radiation pressure, heating, and sublimation interfere with the approach to the surface of solar dust particles, however, as does the pressure of the solar wind. The total value $(M_\odot/M_\odot)_{\text{dust}}$ will therefore be far lower, and the contribution of the dust environment to the material that falls onto the Sun is negligible.

### 4.3.2. Comets and asteroids

The contribution of comets and asteroids to the mass falling onto the Sun may be more considerable than that of dust. A substantial amount of data has been accumulated about objects that were detected or passed in the vicinity of the Sun. Since 1996, permanent observations from the space observatory Solar and Heliospheric Observatory (SOHO) have been made, according to which 4000 comets were discovered by mid-June 2020, most of them very small. Observations of close passages have been obtained from the space observatories: Solar Terrestrial Relations Observatory (STEREO A and B), the Solar Dynamics Observatory (SDO), and the PSP, which reached the solar vicinity in 2019.

Very few of the objects survive close proximity to the Sun. A close passage of the Sun is usually accompanied by partial or severe destruction of the body and the appearance of small fragments (Sekanina & Kracht 2018). Granvik et al. (2016) derived a critical perihelion value $16 R_\odot = 0.074$ AU after which active destruction of asteroids and comets begins to occur.

The perihelia of near-solar comets (Sun-grazing comets) are within $3.5 R_\odot$ (this is inside the Roche limit for liquid bodies). Several comets have been recorded whose trajectories crossed the solar photosphere. Close passes led to the destruction of the comets, sublimation, and ionization, to the loss of mass, momentum, and energy of comets in the solar corona. The cores of most small comets are completely sublimated by solar radiation when they pass in the vicinity of perihelion. The properties of these small objects, mostly owned by the Kreutz Group, have been analyzed (Biesecker et al. 2002; Marsden 2005; Knight et al. 2010; Combi et al. 2019).

Examples for complete destruction and disappearance of the core are the near-solar comets C/2011 N3 (SOHO; Schrijver et al. 2012) and C/2011 W3 (Lovejoy), which were observed by the SDO (Sekanina & Chodas 2012; McCauley et al. 2013). Comet C/2012 S1 ISON experienced significant destruction already on its approach to perihelion (Sekanina & Kracht 2015).

The absence of meter-high fragments in the immediate vicinity of the Sun, according to the PSP observations (Wiegert et al. 2020), is explained by the fact that in the process of destruction near the Sun, asteroids eventually gradually disintegrate to millimeter-sized particles. The destruction of asteroids aids the concomitant erosion of material under the effect of high-speed particles and meteoroids near the Sun. It is difficult for small particles to reach the solar surface because the formed fragments and other small fractions near the Sun experience heating, sublimation, and solar pressure, leading the debris and ejected material of comets and asteroids away from the Sun. A small amount of comet and asteroid matter does impact the Sun.

When small solid bodies (asteroids) approach the Sun, strong radiation and heat effects give off gas molecules, dust particles, and larger regolith particles (Delbo et al. 2014). At small heliocentric distance, for example, for comets near the Sun, the dust quickly dissociates and the gas becomes ionized (Povich et al. 2003; Bryans & Pesnell 2012), and the entire object is often destroyed (Bieseker et al. 2002).

Observations thus indicate that only a small fraction of the substance can reach the solar surface. The rarity of events and the smallness of the bodies themselves indicates that the estimate of the value for the mass falling onto the Sun in our previous works has been significantly overstated. This means that the estimate of the mass falling from comets and asteroids should be significantly reduced compared to previous values (Pitjeva & Pitjev 2012, 2013). The top estimate of the increase in solar mass due to the falling matter of comets in the previous model, as was immediately noted in the paper (Pitjeva & Pitjev 2012), was highly overestimated,

$$M_\odot/M_\odot < 3.2 \times 10^{-14} \text{ per year.}$$

Our new top estimate for the average amount of mass of material falling onto the Sun is

$$M_\odot/M_\odot < 1.0 \times 10^{-14} \text{ per year,}$$

which is reduced by about three times and probably still overestimated by an order of magnitude or more.

### 5. Limits of possible change in gravitational constant $G$

For further estimates, we used the upper and lower bounds of the change rate of solar mass $M_\odot$ due to to radiation and solar wind within a $3\sigma$ error, taking the estimate of the fall of comets and asteroids into account,

$$(M_\odot/M_\odot)_{\text{rad+wind+fall}} = (M_\odot/M_\odot)_{\text{rad}} + (M_\odot/M_\odot)_{\text{wind}} + (M_\odot/M_\odot)_{\text{fall}}.$$  \hspace{1cm} (11)

Taking the estimates for each component of the change rate in solar mass into account, we obtain

$$-13.4 \times 10^{-14} < (M_\odot/M_\odot)_{\text{rad+wind+fall}} < -8.7 \times 10^{-14} \text{ per year.}$$

For the change rate of the solar gravitational parameter $GM_\odot$, we obtained

$$-11.6 \times 10^{-14} < \dot{G}/G + M_\odot/M_\odot < -8.8 \times 10^{-14} \text{ per year(3\sigma).}$$ \hspace{1cm} (13)

From these two inequalities we find a range for a possible change rate in the gravitational constant $G$ per year:

$$-2.9 \times 10^{-14} < \dot{G}/G < +4.6 \times 10^{-14} \text{ year}^{-1}(3\sigma).$$ \hspace{1cm} (14)

The new result, obtained with EPM2019 planetary solution, reffines the ranges of the possible change rate for the gravitational constant $G$ as compared to the previous estimate (Pitjeva & Pitjev 2012), obtained with EPM2010. The estimates of the possible interval for the change in $G$ obtained with different methods and authors in the last eight years are shown in Table 2. The last line shows the result obtained in this work.

### 6. Conclusion

The estimate of the change rate for the solar gravitational parameter $(GM_\odot)$ is obtained from processing modern positional observations of planets and spacecraft. The observations were processed and the parameters determined based on a new version of the planetary ephemeris EPM2019 developed in the IAA RAS.
Table 2. Previous estimates of the change in $G$.

| Authors                          | $s = G/G$ year$^{-1}$ | Comment                                    |
|----------------------------------|-----------------------|--------------------------------------------|
| Pitjev & Pitjev (2012)           | $-4.2 \times 10^{-14} < s < +7.5 \times 10^{-14}$ | Planetary dynamics                         |
| Fienda et al. (2015)             | $|s| < 8 \times 10^{-14}$ | Planetary dynamics                         |
| Hofmann & Müller (2018)          | $s = (7.1 \pm 7.6) \times 10^{-14}$ | Lunar laser ranging (LLR)                  |
| Genova et al. (2018)             | $|s| < 4 \times 10^{-14}$ | Mercury’s MESSENGER mission                |
| Bellinger & Christensen-Dalsgaard (2019) | $s = (2.1 \pm 2.9) \times 10^{-12}$ | Asteroseismology                           |
| Bonanno & Frölich (2020)         | $|s| < 2 \times 10^{-13}$ | Helioseismology                            |
| This paper                       | $-2.9 \times 10^{-14} < s < +4.6 \times 10^{-14}$ | Planetary dynamics                         |

The new planetary ephemeris EPM2019 was constructed using observational data for planets and spacecraft and a refined dynamical model of the Solar System. The dynamical model uses new mass estimates for large bodies of the main asteroid belt and a total mass estimate for small asteroids, their debris, and dust using a new discrete model. A similar refinement was made for the Kuiper belt. The dynamical model includes the combined relativistic Lense-Thirring effect, especially significant for Mercury and Venus, was taken into account.

The observational data include high-precision measurements that are important for this work. They have been obtained relatively recently with the MESSENGER (Mercury) and Juno (Jupiter) spacecraft. A new estimate of the change in solar gravitational parameter $GM_\odot$ was found. Taking into account the estimate for the loss of mass by the Sun averaged over the solar cycle, new restrictions on the change in gravitational constant $G$ from above and below were found. The current annual decrease $\dot{G} = 8.7 \times 10^{-14}$ per year.

The new result reduces the interval for changing $G$ and narrows the possible limits of deviation from general relativity for alternative gravitational theories.

Acknowledgements. The authors thank Dan Aksim for his help with the LaTeX and BibTeX processing of the manuscript.

References

Abbo, L., Ofman, L., Antiochos, S., et al. 2016, Science Rev., 201, 55
Abson, D., & Pavlov, D. 2020, Math. Comput. Sci., 14, 103
Alibert, N., Grün, E., & Landgraf, M. 2016, A&A, 548, 243
Alvey, J., Sabiti, N., Escudero, A., & Howard, R. 2002, Icarus, 157, 323
Bonanno, A., & Frölich, H.-E. 2020, ApJ, 893, 135
Bonanno, A., Esposito, G., & Rubano, C. 2004, Class. Quant. Grav., 21, 5005
Bryans, P., & Pesnell, W. D. 2012, ApJ, 760, 18
Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icarus, 40, 1