

Solar System Expansion and Strong Equivalence Principle as seen by the NASA MESSENGER mission

Antonio Genova^{1,2}, Erwan Mazarico², Sander Goossens^{3,2}, Frank G. Lemoine², Gregory A.
Neumann², David E. Smith¹ and Maria T. Zuber¹

¹Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA (antonio.genova@nasa.gov); ²Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; ³Center for Research and Exploration in Space Science and Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, USA.

The NASA MESSENGER mission explored the innermost planet of the solar system and obtained a rich dataset of range measurements for the determination of Mercury's ephemeris. Here we use these precise data collected over seven years to estimate parameters related to General Relativity and the evolution of the Sun. These results confirm the validity of the Strong Equivalence Principle with a significantly refined uncertainty of the Nordtvedt parameter $\eta=(-6.6\pm 7.2)\times 10^{-5}$. By assuming a metric theory of gravitation, we retrieved the Post-Newtonian parameter $\beta = 1 + (-1.6\pm 1.8)\times 10^{-5}$ and the Sun's gravitational oblateness, $J_{2\odot}=(2.246\pm 0.022)\times 10^{-7}$. Finally, we obtain an estimate of the time variation of the Sun gravitational parameter, $\dot{GM}_{\odot}/GM_{\odot}=(-6.13\pm 1.47)\times 10^{-14}$, which is consistent with the expected solar mass loss due to the solar wind and interior processes. This measurement allows us to constrain $|\dot{G}|/G$ to be less than $4 \times 10^{-14} \text{ yr}^{-1}$.

Introduction

Mercury's role in testing theories of gravitation has always been crucial because the strong gravitational mass of the Sun creates notable perturbations on its orbit. The precession of the closest distance of Mercury to the Sun (perihelion) first highlighted the limits of Newtonian physics and later validated the predictions of Einstein's theory of

31 General Relativity (GR)^[1]. The precession of Mercury's perihelion is primarily due to
32 third-body perturbations from other planets ($\sim 531.63''/\text{Julian century}^{[2]}$), and the
33 relativity effect produces an additional perihelion shift of $\sim 42.98''/\text{Julian century}^{[3]}$. The
34 relativistic corrections to Mercury's heliocentric acceleration can be formulated based on
35 the Parameterized Post-Newtonian (PPN) parameters β and γ , which respectively measure
36 the nonlinearity in superposition of gravity and space-time curvature produced by a unit
37 rest mass. Both parameters are zero in the Newtonian formulation and equal to 1 in GR
38 (see Methods).

39 The Sun's interior structure and dynamics also affect Mercury's trajectory. The
40 solar gravitational oblateness J_2_\odot and the angular momentum S_\odot are responsible for
41 additional precession rates of $\sim 0.029''/\text{Julian century}^{[4]}$ and $\sim 0.002''/\text{Julian century}^{[5]}$,
42 respectively. The latter perturbation, which is known as the gravitomagnetic Einstein-
43 Lense-Thirring (ELT) effect, is related to the distortion of space-time induced by the
44 rotation of the Sun.

45 In practice, strong correlations between γ , β , J_2_\odot and S_\odot limit the combined
46 estimation of these parameters since they all primarily affect Mercury's orbit through the
47 precession of its perihelion. For this reason, a priori assumptions are necessary to
48 disentangle the effect of each parameter. The Nordtvedt parameter η , related to the
49 Equivalence Principle (EP), can be used as a constraint between the PPN parameters γ
50 and β ^[6]. The relationship between these coefficients is:

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$$52 \quad \eta = 4\beta - \gamma - 3 \quad (1)$$

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54 if we assume spatial isotropy, which implies that the PPN parameters α_1 and α_2 are equal
55 to 0.

56 The orbit of Mercury is well-suited to test the EP, which describes the equality
57 between gravitational and inertial masses. The EP has been partially demonstrated by
58 laboratory experiments, to a precision of $\sim 1 \times 10^{-13}$ with recent torsion-balance tests⁷.
59 However, these precise results only concern the Weak Equivalence Principle (WEP),
60 which is based on Galileo's postulate that different objects fall with the same acceleration
61 in a uniform gravitational field, independent of their composition and structure. Einstein
62 extended this concept in his development of GR by introducing the Strong Equivalence
63 Principle (SEP). The SEP states that a uniform gravitational field is locally
64 indistinguishable from an accelerated reference frame⁸. The contribution of the SEP to
65 the gravitational-to-inertial mass ratio depends on the self-gravitational energy (Ω_B) and
66 the rest energy of the body ($m^I c^2$), as follows:

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$$68 \quad \frac{m^G}{m^I} = 1 + \eta \frac{\Omega_B}{m^I c^2} \quad (2)$$

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70 where m^G and m^I are the gravitational and inertial masses, respectively, Ω_B is proportional
71 to $G(m^G)^2 R^{-1}$, G is the gravitational constant, c is the speed of light, and R is the radius
72 of body B , respectively. The Nordtvedt parameter η must be zero to validate the Strong
73 Equivalence Principle. To prove the SEP, the test-mass used in the experiment needs to
74 be sufficiently large so that the self-gravitational force is not negligible. For this reason,
75 tests at the scale of the solar or planetary system are suitable to prove the SEP.

76 The most accurate estimations of η have been retrieved from Lunar Laser Ranging
77 (LLR) over the past 40 years^{9,10,11,12}. The latest solution validates the SEP with an
78 uncertainty of $\sigma_\eta \sim 3.0 \times 10^{-4}$ (Table 1). The coupling of the gravitational attraction of the
79 Sun on the Earth-Moon system with the self-gravitational force of the Earth would
80 provide a significant perturbation in the case of SEP violation. This effect would be
81 measurable with LLR mm-precision data of the Earth-Moon distance¹².

82 An equivalent dynamical effect on Mercury's orbit is due to the coupling between
83 the Sun's self-gravitational force and the gravitational attraction of other planets, mainly
84 Jupiter. However, the main effect that a SEP violation has on the ephemeris of Mercury
85 results from the implied redefinition of the Solar System Barycenter (SSB), which is
86 negligible in the Earth-Moon case (see Methods). A Nordtvedt parameter η of 1×10^{-5}
87 results in discrepancies in the Mercury-Earth relative distance of ~ 3 m after two years¹³.
88 Thus, the knowledge of Mercury's ephemeris to better than 1 m can yield better
89 constraints on possible SEP violations than LLR. Furthermore, this dynamical
90 perturbation of the Nordtvedt parameter is less correlated with other forces and thus
91 separates the effects of $J_{2\odot}$ and β , given the constraint of Eq. 1.

92 The study of Mercury's orbit with a long-duration dataset also gives a unique
93 opportunity to detect the time variation of the gravitational constant G . The estimation of
94 \dot{G}/G is not strongly correlated with other relativistic and solar parameters because its
95 effect is quadratic in time. However, Mercury's orbit is perturbed by the combined effect
96 of secular changes in G and M_\odot as follows:

97

98
$$\dot{GM}_\odot/GM_\odot = \dot{G}/G + \dot{M}_\odot/M_\odot \quad (3)$$

100 where $\dot{M}_{\odot}/M_{\odot}$ is the Sun's mass loss due to solar radiance and wind. A perturbation on
 101 Mercury's orbit induced by a $G\dot{M}_{\odot}/GM_{\odot}$ of 5×10^{-14} , which is $\sim 10\%$ of the Sun's
 102 expected mass loss¹⁴, is on the order of ~ 2 m after 2 years, when projected on the Earth-
 103 Mercury line-of-sight. An estimated time-variation of GM_{\odot} combined with a $\dot{M}_{\odot}/M_{\odot}$
 104 value from heliophysics studies improves the knowledge of \dot{G}/G . Such a study of
 105 heliophysics and relativity requires precise observations of Mercury's position and
 106 velocity over an extended period of time.

107 In this study, we focused on the Radio Science data of the NASA MErcury
 108 Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission to
 109 investigate the interior structure and evolution of the Sun (GM_{\odot} , $J_{2\odot}$, and $\dot{M}_{\odot}/M_{\odot}$) and
 110 theory of gravitation (β , η and \dot{G}/G). Our results show improved estimates of the solar
 111 gravitational oblateness and the mass loss rate that are consistent with helioseismology
 112 and heliophysics theoretical studies, respectively. The accurate measurement of the time
 113 variation of the solar gravitational parameter enabled us to constrain $|\dot{G}|/G$ to be lower
 114 than $4.0 \times 10^{-14} \text{ yr}^{-1}$. Furthermore, we determined the Nordtvedt parameter η with a
 115 refined uncertainty that demonstrates that there are no violations of the Strong
 116 Equivalence Principle at the level of $\sim 6-7 \times 10^{-5}$.

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118 **Results**

119 **MESSENGER and Mercury Combined Orbit Determination**

120 The MESSENGER mission collected spacecraft radio tracking data near Mercury
 121 between January 2008 and April 2015, which are well-suited to improve the ephemeris of

122 the planet¹⁵. These data are range-rate (or Doppler) observables that measure the relative
123 velocity in the line-of-sight between the spacecraft and a Deep Space Network (DSN)
124 Earth station, and range observables of the relative distance between the spacecraft and
125 the DSN station.

126 Doppler observables have been used extensively to determine the trajectory of
127 spacecraft for navigation and geophysical parameter estimation, *e.g.*, the gravitational
128 field of Mercury¹⁶. On the other hand, range observables bear on the knowledge of
129 Mercury's orbit. Range measurements have been analyzed by the Solar System Dynamics
130 Group of the Jet Propulsion Laboratory (JPL), Institute of Applied Astronomy of the
131 Russian Academy of Science, and the Institut de mécanique céleste et de calcul des
132 éphémérides to determine the ephemeris of Mercury, estimating relativistic and
133 heliophysics perturbative forces^{17,18,19,20}.

134 Parallel and independent investigations so far have been conducted to exclusively
135 determine either Mercury's geophysics or its ephemeris. The estimation of Mercury's
136 gravity field relied on the assumption of planet's orbits and GMs, including Mercury,
137 from JPL Development Ephemeris (DE). On the other hand, the ephemeris work
138 processed spacecraft range measurements only by using a pre-converged MESSENGER
139 trajectory. Although both methods have successfully been used for interplanetary orbit
140 determination, their piecemeal combination is not the best approach in the case of
141 Mercury. Systematic errors in the MESSENGER orbits directly enter the range data, and
142 are then absorbed into Mercury's estimated position, since the spacecraft trajectory is not
143 adjusted in the ephemeris solution. Conversely, a mismodeling of Mercury's ephemeris
144 leads to imperfect geophysical solutions.

145 We numerically integrate the spacecraft and planet orbits simultaneously in order
146 to provide a comprehensive solution that includes geophysical, heliophysics, and
147 relativity results together with their associated covariances. Here we focus on the results
148 that provide new information on the interior of the Sun and on gravitational theories.

149 The accuracy of the heliophysics and relativity results largely depends on the
150 precision of the range data. Measurement noise is incurred by the electronics of the Radio
151 Frequency (RF) Telecommunications Subsystem onboard the spacecraft which relays
152 spacecraft telemetry and performs as a radio science instrument²¹. The MESSENGER RF
153 Subsystem operated at X-band frequencies (7.2 GHz uplink, 8.4 GHz downlink) and its
154 two opposite-viewing Phased-Array Antennas (PAAs) were used to conduct the range
155 data campaigns (see Methods).

156 Figure 1 shows the level of noise of the range data collected over the entire
157 MESSENGER mission. Each point represents the range data RMS during each full
158 tracking pass, which usually provides one measurement every 5 minutes for several
159 hours, as a function of the Sun-Probe-Earth (SPE) angle. The relative position of the Sun
160 and Earth during MESSENGER radio observations strongly controls the tracking data
161 quality. The solar plasma causes phase scintillations in the RF signal, increasing the noise
162 of both range-rate and range measurements. At low SPE angles (near superior solar
163 conjunctions), the Sun is located between Mercury and the Earth, and the mean level of
164 noise increases from < 0.5 m for $90^\circ < \text{SPE} < 180^\circ$ to ~ 1.5 m for $35^\circ < \text{SPE} < 90^\circ$ (see Figure
165 1). MESSENGER orbits close to superior solar conjunctions ($\text{SPE} < 35^\circ$) are not included
166 in the solution because of plasma-induced range errors higher than 3 m. The exclusion of
167 these data does not degrade the phase sampling of Mercury's orbit over the full

168 MESSENGER mission. Figure 2 shows a histogram of the number of the processed
169 measurements versus the Mercury orbital phase. A great portion of data was collected in
170 proximity to Mercury’s perihelion and aphelion, enabling precise measurements of the
171 precession induced by solar and relativistic effects. The rest of Mercury’s orbit was
172 evenly sampled, and the level of noise is sufficiently uniform for all orbital phases.

173 This MESSENGER dataset is used to determine at the same time the solar and
174 relativistic parameters that provide fundamental information on the interior structure of
175 the Sun (GM_{\odot} , $J_{2\odot}$, S_{\odot} and $\dot{M}_{\odot}/M_{\odot}$) and theory of gravitation (γ , β , η and \dot{G}/G). Multiple
176 separate experiments have previously established a comprehensive survey of these
177 fundamental physics effects. Table 1 summarizes recent estimates of these parameters.
178 Helioseismology studies^{22,23} enabled precise measurements of S_{\odot} and $J_{2\odot}$, which have
179 been also recovered with ephemerides analysis^{17,18,19,20}. Planetary ephemeris
180 investigations, furthermore, provided the best estimates for β ^{[20],[24],[25]} and
181 $G\dot{M}_{\odot}/GM_{\odot}$ ^{[20],[25]}. Several of these studies do not include the ELT effect, so their
182 estimated $J_{2\odot}$ must be scaled. A more recent determination of Mercury’s ephemeris
183 reported the estimation of $J_{2\odot}$ by accounting for ELT accelerations²⁴. LLR provided
184 accurate estimates of η and \dot{G}/G ^{9,10,11,12}, which has also been determined by astrophysical
185 studies²⁶. The Cassini mission achieved the most precise measurement of the PPN
186 parameter γ through the analysis of radio tracking data near superior solar conjunction²⁷.
187 Although the MESSENGER data are not strongly sensitive to γ and the Sun’s angular
188 momentum, S_{\odot} , this investigation provides a unique opportunity to simultaneously
189 improve the knowledge of GM_{\odot} , $J_{2\odot}$, β , η and $G\dot{M}_{\odot}/GM_{\odot}$.

190

191 **Heliophysics and Relativity Solutions**

192 The main effect of γ on the radio tracking data is the deflection and delay of
193 photons by the curvature of space-time produced by the Sun, and it is best measured at
194 SPE angles lower than 10° . However, this geometry yields high plasma noise so the
195 estimation of the PPN parameter γ with MESSENGER data is not feasible. Given the γ -
196 effect on Mercury's dynamical equations cannot be separated from the dynamical
197 perturbation due to the PPN parameter β nor ignored, γ was thus fixed to 1, while still
198 considering the uncertainty obtained by Cassini²⁷.

199 The strong correlation between Mercury's orbital perturbations due to the Sun's
200 gravitational oblateness and the ELT effect also does not allow the determination of the
201 angular momentum of the Sun with the MESSENGER radio tracking data. The a priori
202 value of S_\odot adopted in this study is $190 \times 10^{39} \text{ kg m}^2 \text{ s}^{-1}$. A covariance analysis shows that
203 the MESSENGER data sensitivity to the ELT effect yields $\sigma_{S_\odot} \sim 40 \times 10^{39} \text{ kg m}^2 \text{ s}^{-1}$, which
204 is ~ 30 times larger than the current best knowledge (Table 1). For this reason, the angular
205 momentum of the Sun is not adjusted, but the ELT effect is of course included in the
206 integration of both the Mercury and MESSENGER orbits. The ELT effect was not
207 modeled in the JPL DE432 ephemerides¹⁸.

208 Our results are based on a global combined estimation of MESSENGER- and
209 Mercury-related orbital dynamics (see Methods). Table 2 shows the a priori and
210 estimated values and uncertainties of the heliophysics and relativistic parameters. The
211 Sun's GM and J_2 estimates are in good agreement with previous works based on
212 Mercury's ephemeris analysis^{20,24,25}. The solar gravitational flattening is notably
213 improved and consistent with helioseismology results, which were based on solar internal

214 rotation measurements^{22,23}. By applying Eq. 1 as constraint, we assume a metric theory of
 215 gravitation. The Nordtvedt relation enables a highly accurate recovery of $J_{2\odot}$ and β
 216 leading to a formal uncertainty of the gravitational flattening refined by, at least a factor
 217 of 3 compared to previous ephemeris studies^{20,24,25}. However, the correlation between $J_{2\odot}$
 218 and β is still high (~ 0.9 , see **Supplementary Table 1**) because the estimation of η is
 219 limited by the accuracy of the range data (see Methods). Four different cases were
 220 studied to assess the effects of a priori knowledge or constraints, if we do not assume a
 221 metric theory of gravitation or if we assume that $\beta-1$, η or both parameters are equal to 0.
 222 These tests generalize our results further and are shown in **Supplementary Table 2**. The
 223 Nordtvedt equation significantly benefits the estimation of β and $J_{2\odot}$ but the η and
 224 $G\dot{M}_{\odot}/GM_{\odot}$ estimates are always stable and near the values shown in Table 2. We note
 225 that an unconstrained solution yields a near-unity $\beta-J_{2\odot}$ correlation and values of $\beta-1=(-$
 226 $1.43\pm 1.47)\times 10^{-4}$ and $J_{2\odot\Box}=(2.10\pm 0.15)\times 10^{-7}$. In case we do not adjust for β and η the
 227 Sun's gravitational oblateness converges to $(2.271\pm 0.003)\times 10^{-7}$ that is still within $\sim 1-\sigma$
 228 of the constrained solution.

229 Both constrained and unconstrained solutions are consistent with Einstein's
 230 theory of General Relativity. GR predictions of β and η values are within $1-\sigma$, as reported
 231 in Table 2. These results enable substantial enhancement of both $\beta-1$ and η estimates,
 232 which are ~ 7 and ~ 5 times closer to 0 than LLR solutions, respectively. The knowledge
 233 of the PPN parameter β in this study is now comparable to the Cassini solution of the
 234 PPN parameter, γ .

235 Furthermore, Table 2 reports the estimation of $G\dot{M}_{\odot}/GM_{\odot}$ that combines the
 236 temporal variations of both G and M_{\odot} . The retrieved negative rate is close to the

237 theoretical computations of the Sun’s mass loss due to interior processes and solar wind.
238 The fusion cycle that generates energy into the Sun relies on the conversion of hydrogen
239 into helium, which is responsible for a solar mass reduction with a rate of $\sim -0.679 \times 10^{-13}$
240 yr^{-1} [28]. On the other hand, the solar wind contribution is more uncertain. The solar cycle
241 significantly influences the solar mass loss rate due to solar wind. Estimates of the mass
242 carried away with the solar wind showed rates between $-(2-3) \times 10^{-14} M_{\odot} \text{yr}^{-1}$ [28],
243 whereas numerical simulations of coupled corona and solar wind models provided rates
244 between $-(4.2-6.9) \times 10^{-14} M_{\odot} \text{yr}^{-1}$ [29]. Therefore, a mean value of the total solar mass
245 loss of $-(0.9-1.1) \times 10^{-13} M_{\odot} \text{yr}^{-1}$ would be expected, since the MESSENGER mission
246 operated during $\sim 2/3$ of an entire solar cycle whose maximum occurred in proximity of
247 the end of the mission.

248

249 **Discussion**

250 The estimated $G\dot{M}_{\odot}/GM_{\odot}$ represents one of the first experimental observations of
251 the solar mass loss. Previous studies have demonstrated the feasibility of estimating this
252 parameter by adjusting the planetary ephemerides^{20,25,28}. Their results, which are
253 consistent with our estimates, were limited by the data availability and possible
254 mismodeling of spacecraft orbits. Our processing of the entire MESSENGER mission
255 increased the solution sensitivity to a variation of $G\dot{M}_{\odot}/GM_{\odot}$, which has a quadratic
256 dependence in time. Furthermore, our new technique, which consists of a double-
257 integration and a combined estimation of both planet and spacecraft orbits, mitigates the
258 systematic errors related to the spacecraft position and velocity.

259 The discrepancy between our solution and the computed $\dot{M}_{\odot}/M_{\odot}$ may be
260 interpreted as an indirect measurement of the universal constant time-variation. The
261 reconstructed \dot{G}/G is lower than $4.0 \times 10^{-14} \text{ yr}^{-1}$ with an uncertainty that is mainly limited
262 by the knowledge of the solar interior evolution ($2\sigma = 5.0 \times 10^{-14} \text{ yr}^{-1}$). This result
263 strengthens the hypothesis that \dot{G}/G is close to 0, improving the estimates of LLR studies
264 by almost an order of magnitude.

265 To validate the accuracy of these results, we reintegrated the orbit of Mercury
266 with our adjusted values. Figure 3 shows the required corrections to the MESSENGER
267 range data to fit at the noise level shown in Figure 1. The red, blue, and green dots are the
268 measurement biases needed with the JPL DE430 and DE432 ephemerides, and our
269 solution, respectively. This plot shows major improvements compared to previous JPL
270 ephemerides. The DE430 Mercury trajectory is affected by 80-m amplitude errors that
271 were corrected in the later DE432, with remaining 5-10 m errors. Our reintegrated
272 ephemeris for Mercury, which is available on the NASA GSFC Planetary Geodynamics
273 Data Archive³⁰, shows only 0.5-3 m biases over the full mission.

274 The stability of Mercury's orbit integration also depends on the ephemerides of
275 the other bodies of the solar system that are provided by the JPL ephemerides. Therefore,
276 we evaluated the changes in recovery of the heliophysics and relativity parameters when
277 using DE430 or DE436 for planetary ephemerides and initial state of Mercury (instead of
278 DE432 previously) and modeling the ephemerides of the asteroids with the JPL
279 AST343DE430¹⁷. These solutions, which are reported in the **Supplementary Table 3**,
280 show consistent results with the estimated values in Table 2. The formal uncertainties do
281 not take into account probable errors in the planets' GM s and trajectories, as they rely

282 only on the measurement accuracies and the correlation among the adjusted parameters.
283 The fourth column of Table 2 shows the maximum estimation differences between the
284 three cases, which rely on the JPL DE430, DE432 or DE436 for the other planet
285 trajectories. These values may be interpreted as conservative uncertainty bounds that
286 account for pessimistic errors due to mismodeling of GM s and orbits of the solar system
287 bodies. The discrepancies between $G\dot{M}_{\odot}/GM_{\odot}$ solutions are slightly larger than the
288 formal uncertainties because of variations in Earth's orbit, Jupiter's GM and orbit, and
289 SSB location between the different JPL DEs that our methodology cannot mitigate.
290 Furthermore, the value of the solar gravitational constant is significantly affected by these
291 discrepancies leading to estimates that are, however, still within 2- and 3- σ s
292 **(Supplementary Table 3).**

293 In conclusion, our analysis of Mercury's ephemeris with the MESSENGER data
294 enhances the knowledge of the relativistic parameter η , confirming predictions of
295 Einstein's theory of GR. We provide one of the first observations of the solar system
296 expansion due to the solar mass loss. The negative rate of $G\dot{M}_{\odot}/GM_{\odot}$ is very close to
297 theoretical computations of the Sun's mass loss rate leading us to significantly constrain
298 the universal constant time-variation. These results are mainly limited by the uncertainty
299 in planet and asteroid ephemerides that perturb Mercury's orbit. We demonstrate the
300 potential of measuring the planets' relative distances over decadal timescales to provide a
301 better understanding of the solar system and Sun evolution. To pursue these challenging
302 scientific goals, future investigations employing precision ranging from a dedicated
303 multi-spacecraft constellation at interplanetary scale may provide a leap in planetary
304 science, heliophysics, and theoretical physics³¹.

305 **Methods**

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307 **Parametrized Post-Newtonian (PPN) formulation**

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The orbital dynamics of planets, satellites and asteroids relies mainly on the

gravitational attraction of the other bodies that are modeled as external point masses.

Nevertheless, Newton's law of universal gravitation needs to be modified to include

Einstein's relativistic corrections by means of the Parametrized Post-Newtonian (PPN) n-

body formalism¹⁷. The acceleration of Mercury due to the interaction with other point

masses is, therefore, given by:

$$\begin{aligned} \mathbf{a}_M^{\text{PPN}} = \sum_{A \neq M} \frac{\mu_A}{r_{MA}^3} (\mathbf{r}_A - \mathbf{r}_M) & \left\{ 1 - \frac{2(\beta+\gamma)}{c^2} \sum_{B \neq M} \frac{\mu_B}{r_{MB}} - \frac{2\beta-1}{c^2} \sum_{B \neq A} \frac{\mu_B}{r_{MB}} + \gamma \left(\frac{v_M}{c} \right)^2 + (1+\gamma) \left(\frac{v_A}{c} \right)^2 - \right. \\ & \left. \frac{2(1+\gamma)}{c^2} \mathbf{v}_M \cdot \mathbf{v}_A - \frac{3}{2c^2} \left[\frac{(\mathbf{r}_A - \mathbf{r}_M) \cdot \mathbf{v}_A}{r_{MA}} \right]^2 + \frac{1}{2c^2} (\mathbf{r}_A - \mathbf{r}_M) \cdot \mathbf{a}_A \right\} + \frac{1}{2c^2} \sum_{A \neq M} \frac{\mu_A}{r_{MA}^3} \{ [\mathbf{r}_A - \mathbf{r}_M] \cdot [(2+2\gamma)\mathbf{v}_M - \\ & (1+2\gamma)\mathbf{v}_A] \} (\mathbf{v}_M - \mathbf{v}_A) + \frac{(3+4\gamma)}{2c^2} \sum_{A \neq M} \frac{\mu_A}{r_{MA}} \mathbf{a}_A \end{aligned} \quad (4)$$

where \mathbf{r}_i , \mathbf{v}_i , \mathbf{a}_i and μ_i are the position, velocity and acceleration vectors with respect to the

SSB, and the gravitational parameter of the body i , respectively, c is the speed of light,

and β and γ are the PPN parameters that measure the nonlinearity in superposition of

gravity and space-time curvature produced by unit rest mass, respectively. This

formulation has been applied to the orbital dynamics of both Mercury and

MESSENGER. The bodies included in these integrations are all major bodies, including

the Sun, Moon, planets, Pluto, and 343 asteroids in the main belt between Mars and

Jupiter. The positions, velocities, accelerations and gravitational parameters are obtained

from the JPL DE432 ephemerides¹⁸ for planets, and the JPL AST343DE430 for

329 asteroids¹⁷. However, to test the stability of the solution, the global estimation was
330 repeated by using JPL DE430 and DE436 ephemerides as a priori. The results of
331 Mercury's ephemeris, GM_{\odot} , $J_{2\odot}$, β , η and $G\dot{M}_{\odot}/GM_{\odot}$ are within the corrected σ reported
332 in Table 2.

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335 **Lense-Thirring Precession**

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337 The dynamical orbital equations of both Mercury and MESSENGER account for
338 the Lense-Thirring effect due to the Sun's gravitomagnetic field that leads to a secular
339 precession of the heliocentric longitude of the ascending node and argument of
340 pericenter.

341 This precession is a prediction of general relativity, and, for this reason, it has
342 been recently renamed as Einstein-Lense-Thirring (ELT) effect. Einstein postulated the
343 frame-dragging in the context of the general theory of relativity stating that non-static
344 stationary distributions of mass-energy affect space-time. In 1918, Josef Lense and Hans
345 Thirring derived the first frame-dragging effect predicting that the rotation of a massive
346 body induces a distortion of space-time. The ELT effect has been measured with the
347 LAGEOS satellites in orbit around the Earth³², and the gyroscopes of the Gravity Probe
348 B³³. A test on ELT effects was initially proposed with the NASA mission Juno in orbit
349 about Jupiter³⁴. The large angular momentum of the planet induces a significant ELT
350 acceleration; however, it is also highly correlated with perturbations due to Jupiter's
351 orientation, which is currently not sufficiently defined³⁵.

352 The ELT effect on Mercury due to the solar gravitomagnetic field is not
 353 negligible, and it may theoretically be used to measure the angular momentum of the Sun.
 354 Mercury's acceleration due to the ELT effect is:

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$$356 \quad \mathbf{a}_M^{\text{ELT}} = \frac{S_\odot G(1+\gamma)}{r_{M\odot} c^2} \left[\frac{3}{r_{M\odot}^2} (\mathbf{r}_{M\odot} \times \mathbf{v}_{M\odot})(\mathbf{r}_{M\odot} \cdot \widehat{\mathbf{p}}_\odot) + (\mathbf{r}_{M\odot} \times \widehat{\mathbf{p}}_\odot) \right] \quad (5)$$

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358 where S_\odot is the angular momentum of the Sun, G is the universal gravitational constant,
 359 $\mathbf{r}_{M\odot}$ and $\mathbf{v}_{M\odot}$ are the heliocentric position and velocity vector of Mercury, respectively,
 360 and $\widehat{\mathbf{p}}_\odot$ is the unit vector of the Sun's pole direction, which relies on the right ascension
 361 $\alpha_\odot=286.13^\circ$ and declination $\delta_\odot=63.87^\circ$ of the pole defined in the International Celestial
 362 Reference Frame (ICRF)³⁶.

363 The ELT effect on Mercury's orbit is mainly in the radial direction with a
 364 maximum acceleration of $\sim 2 \times 10^{-7} \text{ m s}^{-2}$, assuming $S_\odot=190 \times 10^{39} \text{ kg m}^2 \text{ s}^{-1}$. However,
 365 the perturbation induced by the ELT precession is strongly anti-correlated with the effect
 366 due to $J_{2\odot}$, and the recovery of S_\odot is unachievable with the estimation of Mercury's
 367 ephemeris.

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369 **Strong Equivalence Principle**

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371 Milani *et al.*³⁷ formulated, for the first time, a redefinition of the Solar System
 372 Barycenter (SSB) due to violations of the Strong Equivalence Principle (SEP). This effect
 373 causes a significant indirect perturbation on Mercury's orbit that enables an accurate
 374 measurement of η by adjusting the planet's ephemeris. These results provoked a scientific
 375 debate on the consequences of SEP violations for the modeling of planetary ephemerides.

376 Ashby *et al.*³⁸ presented an alternative approach that does not fully include the indirect
 377 perturbation presented by Milani *et al.*³⁷, limiting the contribution of η on planet's orbital
 378 dynamics. However, current planetary ephemerides studies are based on the hypothesis
 379 that the gravitational and inertial masses are equal to compute the SSB location¹⁷.

380 The SSB represents the origin of the ephemerides reference frame. The
 381 assumptions to compute its position are the conservation of mass/energy and the
 382 momentum of the solar system. The SSB is, then, approximated as follows¹³:

383

$$384 \quad \mathcal{R} = \frac{\sum_j \mu_j^* \mathbf{r}_j}{\sum_j \mu_j^*} \quad (6)$$

385

386 where \mathcal{R} is equal to 0 if the SSB is the origin of the reference frame, r_j is the relative
 387 distance of body j with respect to the SSB, and:

388

$$389 \quad \mu_j^* = GM_j^G \left\{ 1 + \frac{1}{2c^2} v_j^2 - \frac{1}{2c^2} \sum_{k \neq j} \frac{GM_k^G}{r_{jk}} \right\} \quad (7)$$

390

391 where GM_j^G is the gravitational mass parameter of body j , r_{jk} is $|r_k - r_j|$ and v_j is the
 392 magnitude of the velocity of body j . This formulation is valid only when the SEP is not
 393 violated ($\eta=0$). The inertial masses should be used in the computation of the SSB, as
 394 follows, if we neglect terms of order $1/c^2$:

395

$$396 \quad \frac{\sum_j M_j^I \mathbf{r}_j}{\sum_j M_j^I} = 0 \quad (8)$$

397

398 where \mathbf{r}_j is the position vector of body j with respect to the SSB, and M_j^I is the inertial
 399 mass of body j . However, these inertial masses are unknown since the masses of the Sun,
 400 planets and satellites are retrieved in space by means of their gravitational pull. A
 401 violation of the SEP may lead to an intrinsic mismodeling of the SSB position. To
 402 account for this effect, the position of the Sun should be redefined by:

403

$$404 \quad \mathbf{r}_\odot = -\frac{1}{\mu_\odot \left(1 - \eta \frac{\Omega_\odot}{M_\odot c^2}\right)} \sum_{j \neq \odot} \left(1 - \eta \frac{\Omega_j}{M_j c^2}\right) \mu_j \mathbf{r}_j \quad (9)$$

405

406 where the sum includes planets and asteroids, Ω_j and M_j are the self-gravitational energy
 407 and the mass of body j , respectively, and the symbol \odot stands for the Sun. The self-
 408 gravitational energy of the Sun, Earth and Moon are -3.52×10^{-6} , -4.64×10^{-10} , and -1.88
 409 $\times 10^{-11}$, respectively^{39,40}. The self-gravitational energy of the other planets is computed by
 410 assuming uniform density $\left(\Omega_j = \frac{3}{5} \frac{GM_j^2}{R}\right)$. We also tested other self-gravitational energy
 411 modeling for the other planets, but the η estimates only changed within 1- σ since the
 412 Sun's self-gravitational energy represents the dominant term.

413 The Sun's position correction (Eq. 9) entails an indirect term in the heliocentric
 414 acceleration of Mercury. The partial derivative of Mercury's heliocentric acceleration
 415 (\mathbf{a}_M) with respect to η , which enables the estimation of this parameter by adjusting the
 416 planet ephemeris, is:

417

$$418 \quad \frac{\partial \mathbf{a}_M}{\partial \eta} \cong \sum_{j \neq M} \mu_j \left(\frac{\Omega_M}{M_M c^2}\right) \frac{\mathbf{r}_{Mj}}{r_{Mj}^3} + \sum_{j \neq \odot} \mu_j \left(\frac{\Omega_\odot}{M_\odot c^2}\right) \frac{\mathbf{r}_{\odot j}}{r_{\odot j}^3} + \sum_{j \neq \odot} \mu_j \left(\frac{\Omega_j}{M_j c^2} - \frac{\Omega_\odot}{M_\odot c^2}\right) \frac{\partial \frac{\mathbf{r}_{M\odot}}{r_{M\odot}^3}}{\partial \mathbf{r}_\odot} \mathbf{r}_j \quad (10)$$

419

420 where the symbol M stands for Mercury, \mathbf{r}_{kj} is the position vector of the relative distance
421 between bodies k and j , \mathbf{r}_{\odot} is the position vector of the Sun with respect to the SSB, and
422 the last term is the indirect effect due to the correction of the SSB position neglecting
423 terms of the order $1/\eta^2$. SEP violations would provide significant perturbations on
424 Mercury's orbit that enable the measurement of η to high accuracy, and decorrelate the
425 PPN parameters and $J_{2\odot}$ if the Nordtvedt equation (Eq. 1) is applied as a priori
426 constraint¹³. However, the correlation between $J_{2\odot}$ and β is still ~ 0.9 even applying the
427 Nordtvedt equation (Supplementary Table 1).

428 This a priori constraint approach was proposed for the first time in the simulations of
429 the relativity experiment that will be conducted by the European Space Agency (ESA)
430 mission BepiColombo¹³. One year of operations in orbit about Mercury will allow
431 BepiColombo to collect 30-cm precision range data for the determination of Mercury's
432 ephemeris. The results of those simulations showed lower correlation between $J_{2\odot}$ and β
433 (~ 0.3) by using the Nordtvedt equation³⁷. The stronger effect of this constraint on the
434 BepiColombo solutions is mainly due to the more precise range data that will enable to
435 determine a more accurate estimate of SEP violations. The accuracy of η estimation
436 affects directly the correlation between $J_{2\odot}$ and β , if the constraint is applied. If we
437 assume the Nordtvedt equation and to know η at the same level of BepiColombo results
438 ($\sim 10^{-6}$), the correlation between $J_{2\odot}$ and β drops to ~ 0.3 that is consistent with the
439 simulation of the future ESA mission to Mercury⁴¹.

440

441 **Time-variable Gravitational Constant**

442

443 The time-varying gravitational parameter $G\dot{M}_\odot/GM_\odot$ is defined by the sum of the
 444 time-variations of the gravitational universal constant \dot{G}/G and the mass of the Sun
 445 \dot{M}_\odot/M_\odot . The additional term of Mercury's heliocentric acceleration due to $G\dot{M}_\odot/GM_\odot$
 446 is:

$$448 \mathbf{a}_M^{G\dot{M}_\odot} \cong GM_\odot \left(\frac{G\dot{M}_\odot}{GM_\odot} \Delta t \right) \frac{\mathbf{r}_{M\odot}}{r_{M\odot}^3} \quad (11)$$

449
 450 where Δt is the difference between the current epoch and the reference epoch J2000 (1
 451 January 2000 at 12:00 UTC), and $\mathbf{r}_{M\odot}$ is the relative position vector between Mercury
 452 and the Sun.

453
 454
 455 **Ephemeris and Orbit Determination**
 456

457 The results presented in this paper were obtained with the NASA Goddard Space
 458 Flight Center (GSFC) orbit determination software GEODYN II, which has been used to
 459 determine geophysical parameters of, for example, the Earth, Moon and Mars. We used
 460 GEODYN II to recover previous solutions of Mercury's gravity field, orientation and
 461 tides assuming the JPL DE430 ephemeris of Mercury¹⁷. To estimate Mercury's
 462 ephemeris and the associated heliophysics and relativity parameters, we modified
 463 GEODYN II to numerically integrate the orbits of both MESSENGER and the planet
 464 Mercury simultaneously.

465 This software is based on a batch least-squares scheme that allows the
 466 combination of all observations within one batch (arc) for the estimation of the
 467 parameters of interest. The least-squares technique relies on an adjustment of model

468 parameters to minimize the discrepancies between the computed observables and actual
469 measurements (residuals). If the trajectory of the spacecraft alone is integrated, the only
470 parameters that can be estimated are related to MESSENGER's dynamics around
471 Mercury (e.g., the gravity field of the planet). The simultaneous numerical integration of
472 the planet ephemeris allows the adjustment of other model parameters, such as those from
473 heliophysics and relativity that perturb the orbit of Mercury.

474 The MESSENGER orbital mission (2011-2015) was partitioned in 1499 one-day
475 arcs. Three additional ~ 10 -day arcs cover the three Mercury flybys in 2008-2009. The
476 range data were weighted according to the contribution of the solar plasma that varied
477 through the mission as expressed by the Sun-Earth-Probe angle. For each arc, the
478 Mercury's ephemeris is continuously integrated from the Flyby 1 initial epoch (7 January
479 2008 at 00:00 UTC). We generated partial derivatives of the following MESSENGER-
480 related parameters: spacecraft initial states, areas of the spacecraft sunshield and solar
481 panels, Mercury's gravity field up to degree and order 100 in spherical harmonics, and
482 Mercury's Love number k_2 and orientation (pole's right ascension and declination). We
483 also computed partial derivatives of the following Mercury-related parameters: planet's
484 initial state, GM_{\odot} , $\dot{GM}_{\odot}/GM_{\odot}$, $J_{2\odot}$ and S_{\odot} , PPN parameters β and γ , and Nordtvedt's
485 parameter η .

486 The individual normal equations of all these arcs were combined and inverted to
487 yield the final estimates of the geophysical, heliophysics and relativity parameters. The
488 orbit of the Earth is not integrated and adjusted in this study since the orbital accuracy of
489 the Earth from the JPL DE432 ephemerides is comparable to the precision of the
490 MESSENGER data.

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493 **MESSENGER Data set**

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496 The data processed in this paper include the three MESSENGER flybys around
497 Mercury, and the whole orbital mission. The three flybys occurred on 14 January 2008, 6
498 October 2008, and 29 September 2009, respectively. MESSENGER was inserted in a
499 highly eccentric and near-polar orbit about Mercury on 18 March 2011. The initial period
500 was ~12 h and the orbital periapsis was at ~200-km altitude and ~60°N latitude. Orbit-
501 Correction Maneuvers (OCMs) were required to maintain the periapsis between 200 and
502 500 km for the first year of operations. The third body perturbation of the Sun combined
503 with the high eccentricity of the orbit led to a significant drift of the periapsis altitude and
504 latitude.

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516 The mission was extended for a second year in March 2012. The OCMs became
517 less frequent, and one of them was used to reduce the orbital period to ~8 h. A second
518 extended mission (XM2) started in March 2013 and included a low-altitude campaign
519 until Mercury impact on 28 April 2015. The fuel reserves enabled the spacecraft to
520 maintain periapsis altitudes as low as 15-25 km for several weeks. NASA's DSN stations
521 tracked the spacecraft during part of these passages from April to October 2014 leading
522 to accurate measurements of Mercury's gravity at altitudes between 25 and 100 km. In
523 the last six months of the mission, the closest approaches of MESSENGER were occulted
524 by Mercury and were thus not visible from the Earth. However, additional range-rate and
525 range measurements were collected at low altitudes between 75 and 100 km.

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536 The data included in this study were collected over ~900 days. The greater part of
537 the excluded data is because of high levels of plasma noise in proximity of superior solar

516 conjunctions ($SPE < 35^\circ$). Other arcs were also omitted because of the presence of OCMs
517 or Reaction Wheel Momentum Desaturation Maneuvers that imparted significant ΔV s
518 leading to significant orbital errors.

519

520

521 **Range-Rate and Range Measurements**

522

523

524 The analysis of the range data to estimate Mercury's ephemeris relies strongly on
525 the accuracy of MESSENGER orbital reconstruction. The data collected during XM2,
526 especially, are very sensitive to the quality of the spacecraft orbits. Uncompensated
527 gravity anomalies of Mercury's gravity field may affect significantly the range residuals
528 leading to inaccurate ephemeris solutions. To mitigate the effects of MESSENGER
529 orbital errors in the determination of Mercury's ephemeris, both range-rate and range
530 data have been analyzed in this study. This dataset includes two-way and three-way
531 coherent range-rate and two-way coherent range measurements. The difference between
532 two- and three-way data is only related to the receiving station. The signal is transmitted
533 by the DSN station and sent coherently back to the same (two-way) or a different (three-
534 way) station by the spacecraft Deep Space Transponder (DST). The two-way
535 configuration guarantees highly accurate data thanks to the H-masers at the DSN ground
536 stations. The 3-way data require additional bias corrections due to the time delay between
537 the oscillators at the transmitting and receiving stations. The biases of the 3-way range-
538 rate data are adjusted in the solution to mitigate this error source.

538 The Earth-spacecraft radio link was supported by diametrically opposite-facing

539 Phased-Array Antennas (PAAs) for the high-gain downlink signal, and two fanbeam

540 antennas to provide medium-gain uplink and downlink. Four Low-Gain Antennas

541 (LGAs) were also used to enable the instrumentation pointing towards the planet surface
542 during tracking periods. However, the range data campaigns were always conducted with
543 the front and back PPAs, as shown in Figure 1. The gain level of the antennas influences
544 significantly the level of noise of the range-rate data²¹. A major source of error for the
545 range data is the internal spacecraft delay that was measured during ground testing with
546 an uncertainty of ~12-14 ns that leads to a range accuracy of less than 2 m^[21]. Further
547 tests in flight enabled to reconstruct a more precise delay time, which was necessary for
548 science operations at Mercury. MESSENGER operated for ~11 years in space, and its
549 instrumentations, including the transponder, coped with the effects of ageing. By
550 interpolating the range data residuals, we were able to determine a linear trend of the time
551 delay that is probably associated with the ageing of the spacecraft transponder. The rate
552 of the mean time delay is ~0.45 ns (~13.5 cm) per year, which provides a maximum
553 offset of < 1 m between January 2008 and April 2015. This effect is within the level of
554 accuracy of the range data (1-2 m) that was retrieved during test laboratory results²¹.

555 Another source of range data error is given by station biases due to imperfect
556 calibration. The accurate measurement of the ranging signal round-trip delay is made
557 through digital signal processors at the DSN stations by correlating the uplink and
558 downlink carriers that are coherently related. This calibration may lead to biases on the
559 measured delay with a standard deviation of 1-3 m. To mitigate these calibration errors,
560 range station biases for each tracking pass may be estimated in orbit determination.
561 However, the estimation of the range station biases tends to absorb the uncompensated
562 ephemeris mismodeling. For this reason, the range station biases are not estimated in this
563 study of Mercury's ephemeris, heliophysics and general relativity.

564 These biases may instead be used to determine the quality of the ephemeris
565 results. After convergence of the global solution, all the adjusted parameters (see
566 Ephemeris and Orbit Determination) are applied in a final iteration, in which the range
567 station biases are adjusted instead of the Mercury's initial state, GM_{\odot} , $J_{2\odot}$, β , η and
568 $\dot{M}_{\odot}/GM_{\odot}$. Figure 3 shows the retrieved station biases that are within the expected
569 range of calibration errors. To compare the quality of these results, Figure 3 shows the
570 range biases estimated by using JPL DE430 and DE432 original settings.

571
572 **Data availability**

573 The MESSENGER radio tracking data are available from the NASA Planetary
574 Data System archive (<http://pds-geosciences.wustl.edu/missions/messenger/rs.htm>). The
575 retrieved ephemeris of Mercury is available on the NASA GSFC Planetary Geodynamics
576 Data Archive (ref. 30).

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704

705 **Acknowledgements**

706 This work was conducted at the NASA Goddard Space Flight Center. We are grateful to

707 J.B. Nicholas (EST, Inc.), D.E. Pavlis (SGT, Inc.), and D.D. Rowlands (NASA, GSFC)

708 for their help with the GEODYN II software. A.G. thanks L. Iorio (MIUR), and A.

709 Milani, (University of Pisa) for ideas and discussions. The data used in this paper are

710 available at <http://pds-geosciences.wustl.edu/missions/messenger/rs.htm>.

711

712 **Author Contributions**

713 A.G., E.M., and S.G. performed radio tracking data processing and preliminary analysis

714 of the MESSENGER orbits. A.G. developed updated relativistic and solar modeling in

715 the NASA GSFC orbit determination software (GEODYN II). All co-authors contributed

716 to the interpretation of the results and to writing the paper.

717

718 **Competing interests**

719 The authors declare no competing financial interests.

720 **Corresponding author**

721 Correspondence to Antonio Genova.

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727 Figure 1 Noise level of the MESSENGER range data. RMS of range measurements as a function of the
728 Sun-Probe-Earth angle, which illustrates the effect of the solar plasma on the data noise. Lower SPE angles
729 produce higher noise since the signal passes through dense solar plasma closer to the Sun. The data
730 collected near superior solar conjunction ($SPE < 35^\circ$) were not included in the analysis. The figure also
731 shows the antennas that were used to provide the downlink to the DSN station. The range data were always
732 collected during tracking passes with fanbeam for uplink and PPAs for downlink reducing thermal noise
733 effects.

734
735 Figure 2 Data distribution throughout Mercury's orbit. Number of the analyzed measurements as function
736 of the Mercury distance from the Sun in Astronomical Units (AU). Colors indicate the noise level
737 distribution during each phase bin of Mercury's orbit. The greater part of the data was collected close to
738 Mercury's perihelion and aphelion.

739
740 Figure 3 Temporal distribution of the range biases with three Mercury's ephemeris. The measurement
741 biases are required to fit the MESSENGER range data at the noise level with the JPL DE430 (red) and
742 D432 (blue) ephemerides, and our integrated trajectory for Mercury (green). These biases were used to
743 determine the quality of the ephemeris results. After convergence of the global solution, all the adjusted
744 parameters (see Methods) are applied in a final iteration, in which the range biases are adjusted instead of
745 the Mercury's initial state, GM_\odot , $J_{2\odot}$, β , η and \dot{GM}_\odot/GM_\odot . Large range biases suggest significant errors
746 in the planet's ephemeris.

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	<i>Recent Values</i>	<i>References</i>
$GM_{\odot} (km^3 s^{-2})$	132712440043.754±0.14	Latest solution of the INPOP (Intégration Numérique Planétaire de l'Observatoire de Paris) planetary ephemerides ²⁰ .
	2.30±0.25	
$J_{2\odot} (\times 10^{-7})$	2.20±0.03	Helioseismology result based on the theory of slowly rotating stars ²² .
$S_{\odot} (\times 10^{39} kg m^2 s^{-1})$	190±1.5	Helioseismology result with satellite and Earth-based measurements ²³ .
$\gamma-1$	$(2.1\pm 2.3) \times 10^{-5}$	Cassini superior solar conjunction experiment ²⁷ .
$\beta-1$	$(-6.7\pm 6.9) \times 10^{-5}$	Numerical estimation with INPOP13c ²⁰ .
	$(1.2\pm 1.1) \times 10^{-4}$	Lunar Laser Ranging (LLR) experiment ¹¹ .
η	$(1.0\pm 3.0) \times 10^{-4}$	LLR analysis based on refined modeling ¹² .
	$(1.0\pm 2.5) \times 10^{-13}$	
$\dot{G}/G (yr^{-1})$	$(6.0\pm 11.0) \times 10^{-13}$	21-year timing of the millisecond pulsar J1713+0747 ^[26] .
	$< 0.8 \times 10^{-13}$	INPOP ^[20] and Ephemerides of the Planets and the Moon (EPM2011) ^[25] .
$\dot{GM}_{\odot}/GM_{\odot}(yr^{-1})$	$(-0.50\pm 0.29) \times 10^{-13}$	INPOP ^[20]
	$(-0.63\pm 0.43) \times 10^{-13}$	EPM2011 ^[25]
$\dot{M}_{\odot}/M_{\odot}(yr^{-1})$	$(-1.124\pm 0.25) \times 10^{-13}$	Combined estimation of Sun's luminosity and solar wind ^{**} .

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Table 1 Current knowledge of General relativity and heliophysics parameters. These quantities were

761 obtained from a variety of dedicated investigations, including helioseismology and LLR experiments. The

762 uncertainties reported in the table are 1- σ . The GM_{\odot} and $J_{2\odot}$ adopted in this study as a priori are the JPL

763 DE432 values, $GM_{\odot} = 132712440041.9394 km^3/s^2$ and $J_{2\odot} = 2.1890 \times 10^{-7}$, which were reported without

764 formal uncertainties. The $\dot{M}_{\odot}/M_{\odot}$ value is given by the mass loss rates induced by Sun's luminosity

765 $\dot{M}_{\odot}/M_{\odot} = -0.679 \times 10^{-13} yr^{-1}$ ^[28] and solar wind $\dot{M}_{\odot}/M_{\odot} = -(0.2-0.69) \times 10^{-13} yr^{-1}$ ^{[28],[29]}, respectively. The

766 uncertainty is mainly related to the solar wind contribution.

	<i>A priori Values</i>	<i>Estimated Values</i>	<i>Formal Uncertainties</i>	<i>Sensitivity to Change of Planetary Ephemerides</i>
$GM_{\odot} (km^3 s^{-2})$	132712440041.9394	132712440042.2565	0.35	0.87
$J_{2\odot} (\times 10^{-7})$	2.1890	2.246	0.02	0.02
$\beta-1 (\times 10^{-5})$	0	-1.625	1.8	1.57
$\eta (\times 10^{-5})$	0	-6.646	7.2	6.24
$\dot{GM}_{\odot}/GM_{\odot} (\times 10^{-14} yr^{-1})$	0	-6.130	1.47	3.14

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Table 2 A priori and estimated values, and uncertainties from the global estimation of the GR and

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heliophysics parameters. The formal uncertainties are given by the covariance matrix of the least-square

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solution, which does not include possible mismodeling of GMs and states of the other planets, and asteroids

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of the solar system. The third column reports the maximum discrepancies between solutions that we

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obtained by using the JPL DE430, DE432 or DE436 ephemerides to model the third-body perturbation of

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the planets. The ephemerides of the asteroids are based on the JPL AST343DE430^[17] for the three cases.

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