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Solar Gravitational Radiation Reflected on the Hydrogen Wall might explain the Pioneer Anomaly: Do Mirrors for Gravitational Radiation Exist?

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***Abstract* — The Hydrogen wall found in the Voyager 1 data was modeled as the spherical mirror reflecting the Solar gravitational radiation back to the Solar System. A similar proposal appeared in the forgotten publication of Jaumann in 1912. The formula describing the anomalous acceleration of Pioneer 10 and 11 towards the Sun was derived. The decreasing temperature in the Solar System decreases slightly the mass of both Pioneers 10 and 11 as it was predicted by Einstein in 1907. The experimental value for both Pioneers was published as $a_p = (8.74 \pm 1.33) * 10^{-10}$ ms^{-2}. This new model predicts the value of the anomalous acceleration towards the Sun as $a_p = (8.50 - 0.0106 * x) * 10^{-10}$ ms^{-2} AU^{-1} where x is the distance of Pioneers from the Sun in astronomical unit AU. The annual amplitude visible in the Pioneer data (~ $1.6 * 10^{-10}$ ms^{-2}) was interpreted as the reflection of the Earth´s gravitational radiation from the surface of the Sun – the Earth´s self-gravitational effect with the predicted value $1.49 * 10^{-10}$ ms^{-2}. The diurnal amplitude visible in the Pioneer anomaly (~ $3 * 10^{-12}$ ms^{-2}) was interpreted as the result of Newton´s third law – for every action, there is an equal and opposite reaction between the Sun and the Earth: the diurnal amplitude was derived as $3.05 * 10^{-12}$ ms^{-2}. It will be very helpful to get more experimental data from the next missions towards the Termination shock, the Hydrogen wall using the spacecraft of the type Voyager and Pioneer.**

***Keywords* —** Annual Amplitude, Diurnal Amplitude, Hidden Gravitational Force, Hydrogen Wall, Pioneer Anomaly, Solar Gravitational Radiation.

I. Introduction

During the missions of Pioneer 10 and 11 at the heliocentric distances of 20 – 70 AU, a small, anomalous, blue-shifted frequency shift was observed. This drift was interpreted as a constant acceleration towards the Sun at the level $a_p = (8.74 \pm 1.33) * 10^{-10}$ ms^{-2}, e.g. [1]-[12]. There appeared many papers searching for a hidden gravitational force in the Solar System, e.g. [13]-[34] but no model could successfully explain the experimental data visible in the Pioneer anomaly. Turyshev and Toth (two co-workers of Anderson who discovered the Pioneer anomaly around the year 1980) closed this discussion with the interpretation that the recoil force associated with an anisotropic emission of thermal radiation of the vehicles caused that Pioneer anomaly [12], [35]. On the other side, the discoverer of the Pioneer anomaly Anderson did not accept this interpretation and tried to develop some other models [36], [37]. Based on intuition of Anderson, we think that the door for further research should be open as stated by Gillies [38]: "The door must always be left open to the possibility that new gravitational effects may be discovered by future experiments or revealed from re-analysis of old ones".

II. The Hydrogen Wall as the Spherical Mirror for the Solar Gravitational Radiation

Count von Stürgkh (1859-1916) had entangled Einstein (1879-1955) with Jaumann (1863-1924) in 1910 [39], [40]. In order to explain small deviations from the Newton´s gravitational law Einstein developed his model with the curved space-time [41]. On the other side, Jaumann tried to discover a hidden gravitational force in the Solar System to explain these small gravitational deviations. We were inspired by this Jaumann´s quote; (…) *only an aether sphere of such immense radius that when passing through it the Solar light is completely absorbed, had the same and opposite gravitational effect towards the outside as the Sun* [42].

The Voyager 1 and 2 missions provided unique information on the heliospheric boundary owing to their direct measurements of the Lyman α signal. The main source of the heliospheric Lyman α emission is

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scattering of solar photons by the interstellar hydrogen atoms. Katushkina *et al.* [43] published the very valuable study "Voyager 1/UVS Lyman α measurements at the distant Heliosphere (90-130 AU): unknown source of additional emission" where their model of the Hydrogen wall was presented in Fig. 1.

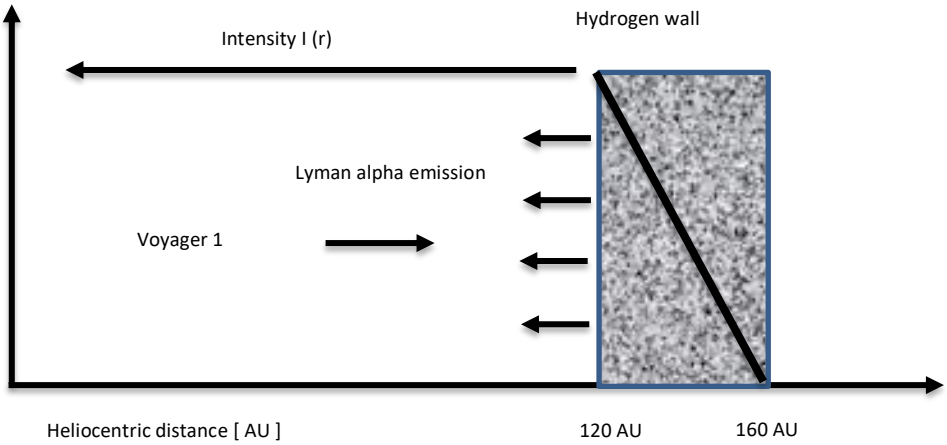

Fig. 1. The model of the Hydrogen wall based on the Lyman α intensity backscattered at a dense layer with significantly Doppler-shifted H atoms in Katushkina *et al.* [43].

Based on these experimental data we proposed a new model of the spherical Hydrogen wall that might serve as the mirror for the Solar gravitational radiation as shown in Fig. 2. Minter, Wegter-McNelly and Chiao formulated the question: "Do mirrors for gravitational waves exist?" [44].

For the quantitative calculations with this "hidden" gravitational force acting on the Pioneer 10 and 11 spacecrafts we have to determine the volumes of two spherical caps with the reflected Solar gravitation field as shown in Fig. 3.

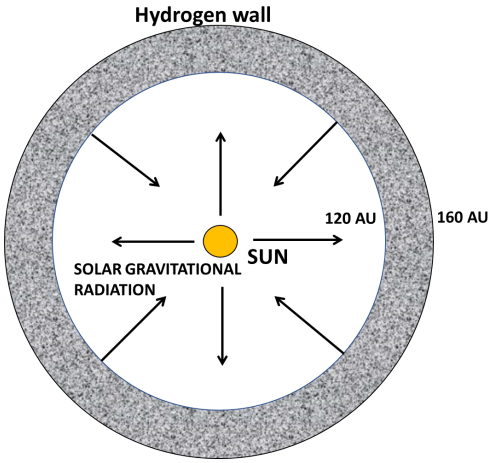

Fig. 2. The Solar gravitational radiation reflected on the Hydrogen wall – the model of the "hidden" gravitational force in the Solar System.

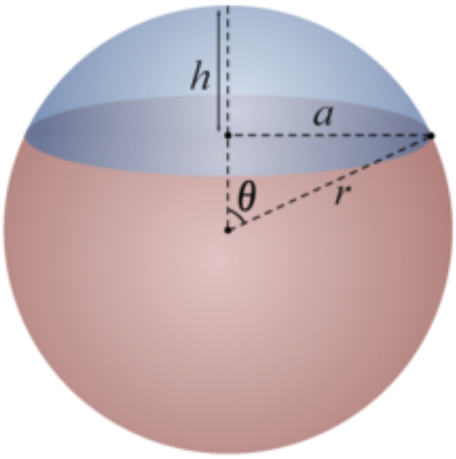

Fig. 3. Two spherical caps with the reflected Solar gravitational radiation, r = 120 AU, h = 120 – x (x is the heliocentric distance of the Pioneer spacecrafts in AU) [45].

The contributions of volumes V_1 and V_2 of two caps with the radius r = 120 AU and the height h = 120 – x, where x is the heliocentric distance in AU of the Pioneer 10/11 spacecrafts, can be evaluated using (1) and (2).

$$V_1 = \frac{\frac{\pi h^2}{3}(3r-h)}{\frac{2\pi}{3}r^3} = \frac{(120-x)^2\left[3*120-(120-x)\right]}{2*120^3} \quad (1)$$

$$V_2 = 2 - V_1 \quad (2)$$

III. The "Hidden" Solar Gravitational Force

The additional acceleration a_{HW} of the Pioneer 10/11 spacecraft towards the Sun influenced by the reflected Solar gravitational radiation on the Hydrogen wall (HW) can be calculated from Newton´s famous formula:

$$a_{HW} = \frac{\frac{GM_{\odot}}{R_{AU}^2 (2*120+x)^2} * V_2 - \frac{GM_{\odot}}{R_{AU}^2 (2*120-x)^2} * V_1}{x} \left[m\, s^{-2} AU^{-1} \right] \quad (3)$$

where G is the Newtonian gravitational constant, $M_{\odot}$ is the mass of the Sun, R_{AU} is the astronomical unit in meters, V_1 and V_2 are the spherical cap contributions, and x is the heliocentric distance in AU.

From (3) we will get the additional acceleration of the Pioneer 10/11 spacecrafts towards the Sun depicted in Figure 4.

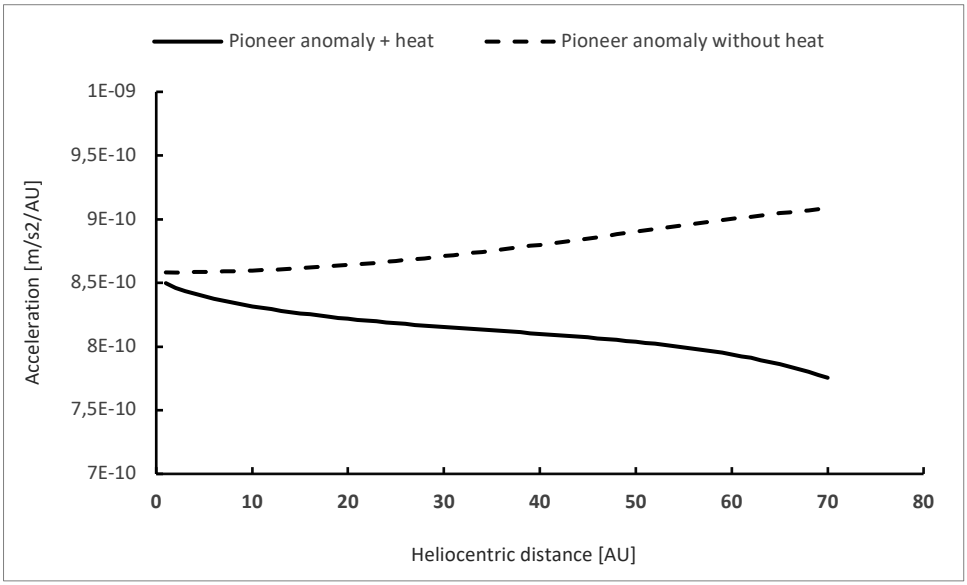

Fig. 4. The Pioneer anomaly: dashed line calculated from (3) (no heat effect on the mass of Pioneer 10/11), full line calculated from (8) with heat effect on the mass of Pioneer 10/11.

There are two new effects: 1) the decreasing temperature in the Solar System decreases the mass of the Pioneer 10/11 spacecrafts, 2) the gravitational constant of the reflected Solar gravitation radiation could be described as G/x in units $m^3\ kg^{-1}\ s^{-2}\ AU^{-1}$.

IV. The Influence of Temperature on the Mass

There are two theoretical predictions of the influence of temperature on the mass. Einstein in 1907 based on the special relativity predicted for water molecules the value $4.6 * 10^{-14}$ kg kg^{-1} K^{-1} [46]. Assis and Clemente in 1993 based on the Dulong-Petit law and the Weber´s force law predicted the value $\approx 10^{-14}$ kg kg^{-1} K^{-1} [47].

Therefore, it is very difficult to experimentally verify those predictions in the Earth´s laboratories. Martins [48], [49] surveyed those experimental attempts to get the experimental value for the influence of temperature on the mass. These experimental results are summarized in Table I.

TABLE I: The Experimental Determination of the Mass Dependence on Temperature

Year	Authors	$\lvert\gamma\rvert$ [kg kg^{-1} K^{-1}]	Reference
1799	Thomson	$< 10^{-6}$	[50]
1905	Poynting and Phillips	$< 2*10^{-10}$	[51]
1906	Southerns	$< 10^{-8}$	[52]
1919	Pettersson	$< 10^{-9}$	[53]
1923	Shaw and Davy	$< 2*10^{-6}$	[54]
2010	Tajmar et al.	$< 2*10^{-8}$	[55]
2020	Tajmar et al.	$< 1.8*10^{-8}$	[56]

We have now a good possibility to extract such tiny values from the Pioneer anomaly. Is there any mass dependence of those spacecrafts on the temperature of the Solar System? Stávek modeled the temperature in the Solar System using the Stefan-Boltzmann law [57]. In this model the Solar radiant heat was reflected

on the Termination shock at the distance R_{TS} = 102.3 AU in order to get at 1 AU the observed temperature of the microwave background radiation in thermal telescopes.

The temperature in the direction towards to the Termination shock $T_{FORWARD}$ might be modeled as (4) [57].

$$T_{FORWARD} = 278.84\left(\frac{1}{x}\right)^{0.5} \tag{4}$$

The temperature reflected on the Termination shock T_{BACK} might be modeled as (5) [57].

$$T_{BACK} = 27.568\left(\frac{1}{102-x}\right)^{0.5} \tag{5}$$

During the long path of Pioneer 10/11 through the Solar System the surrounding space temperature cools down both spacecrafts on the dependence of the heliocentric distance from the Sun and we can expect some mass decrease of those spacecraft. The proposed model is expressed in (6).

$$-a_{HEAT} = \frac{\frac{GM_{\odot}}{R_{AU}^2(2*120+x)^2}*V_2 - \frac{GM_{\odot}}{R_{AU}^2(2*120-x)^2}*V_1}{x} * \frac{T_{BACK}}{T_{FORWARD}} \tag{6}$$

This decrease of the spacecraft mass kg/kg should decrease the total value of the Pioneer anomaly and is registered as $-a_{HEAT}$ in Fig. 5.

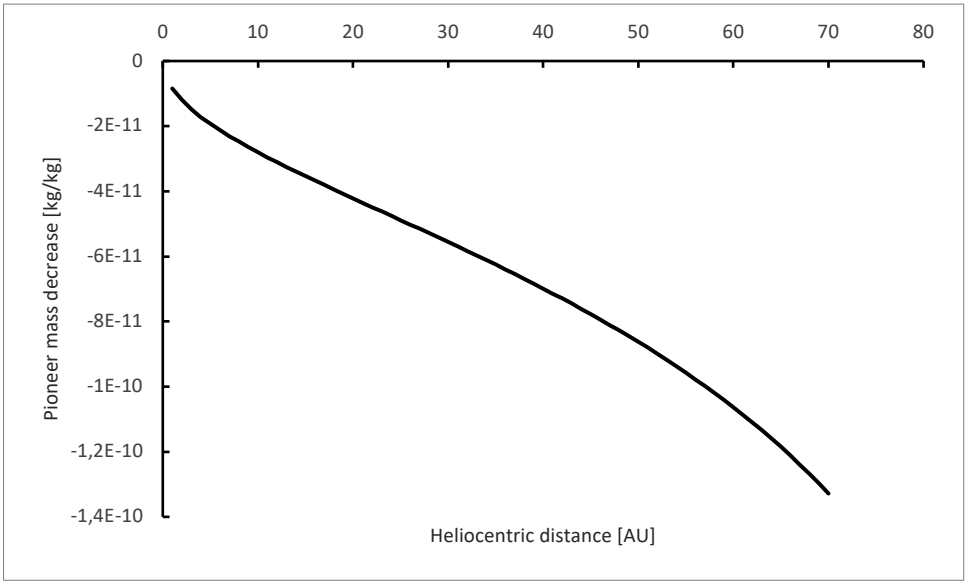

Fig. 5. The predicted mass decrease of the Pioneer 10/11 spacecrafts should be visible in the Pioneer anomaly.

The specific mass decrease of the Pioneer 10/11 spacecrafts in kg/kg/K can be evaluated from (7), at the distance 1 AU we will obtain the value $-3.03*10^{-14}$ kg/kg/K which agrees with both Einstein and Assis-Clemente predictions:

$$\frac{\Delta m}{m_0 T_{FORWARD}} = \frac{\frac{GM_{\odot}}{R_{AU}^2(2*120+x)^2}*V_2 - \frac{GM_{\odot}}{R_{AU}^2(2*120-x)^2}*V_1}{x} * \frac{T_{BACK}}{T_{FORWARD}^2} \tag{7}$$

The total value of the Pioneer anomaly a_P should be calculated by (8) and is shown in Fig. 4:

$$a_P = a_{HW} + (-a_{HEAT}) \tag{8}$$

Fig. 6 depicts the specific mass decrease in kg/kg/K on the dependence of the heliocentric distance from the Sun.

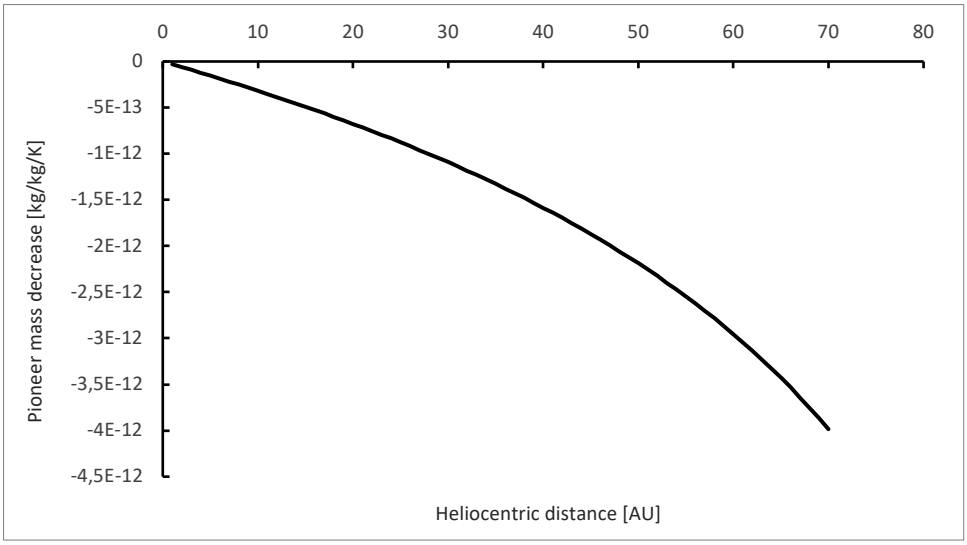

Fig. 6. The predicted specific mass decrease in kg/kg/K of the Pioneer 10/11 spacecrafts depends on the heliocentric distance.

V. The Model and the Real Pioneer Anomaly

There were published two results of the Pioneer anomaly. The first value $a_p = (8.74 \pm 1.33) * 10^{-10}$ ms^{-2} became the standard value for all analysis around the year 2004. The second result in 2012 [35] explained the Pioneer anomaly as the recoil force associated with an anisotropic emission of thermal radiation of the vehicles and closed the further activity of other scholars. We present the model with the expression for the Pioneer anomaly as $a_P = (8.50 - 0.0106 * x) * 10^{-10}$ m s^{-2} AU^{-1} where x is the heliocentric distance in AU The comparison of the model with the experimental data is given in Figure 7 and Figure 8.

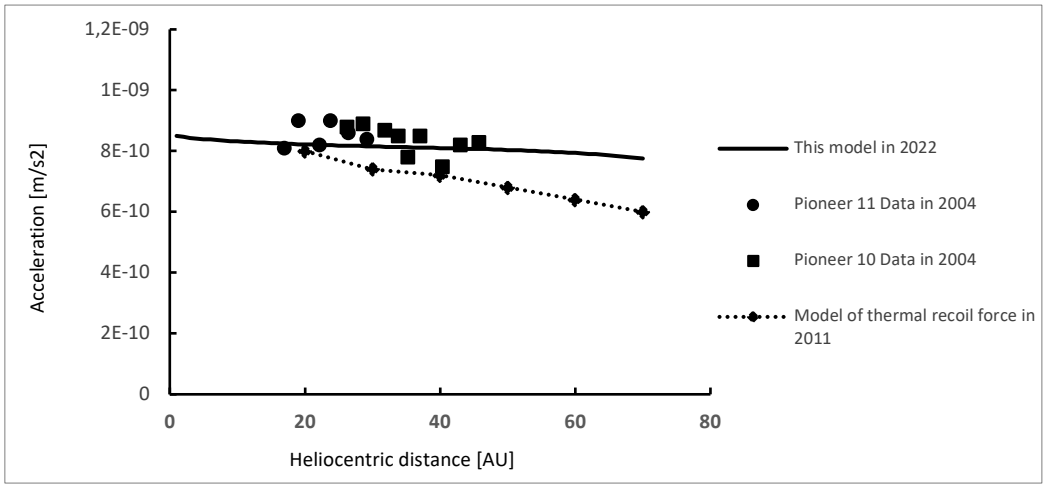

Fig. 7. The experimental data of the Pioneer anomaly in the year 2004 [4],
the thermally induced force in 2011 [35], the model in 2022.

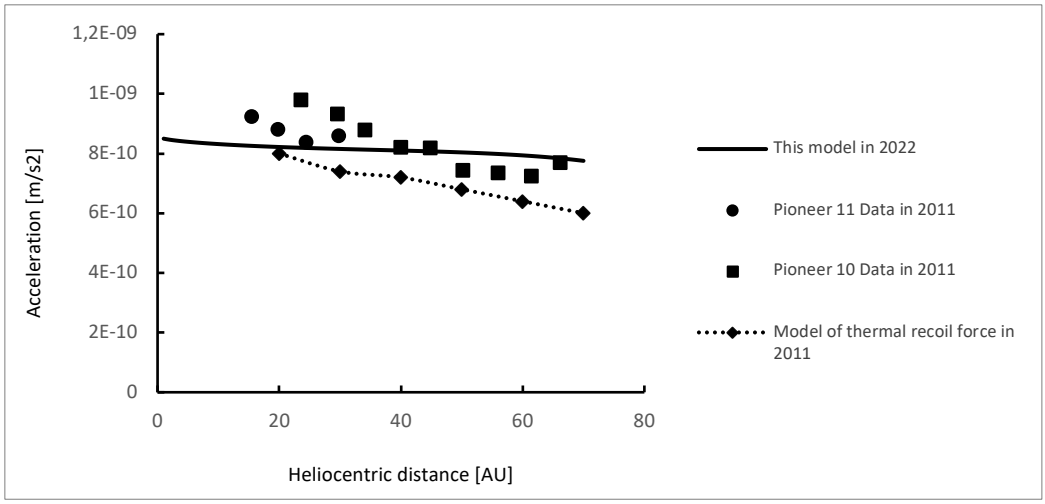

Fig. 8. The experimental data of the Pioneer anomaly in the year 2012 [37]
the thermally induced force in 2011 [35], and this model in 2022.

VI. The Annual and Diurnal Amplitudes in the Pioneer Anomaly

In addition to the constant anomalous acceleration a_P, Anderson and his co-workers observed the annual amplitude on the level ~ 1.6 * 10^{-10} ms^{-2} and the diurnal amplitude on the level ~ 3 * 10^{-12} ms^{-2} [58]. Anderson et al. concluded that these annual and diurnal amplitudes are not spacecraft-related phenomena nor artifacts of the measuring devices and modeling, but they are some Earth-related phenomena. There were published several attempts to explain these observed amplitudes, e.g. [6], [32], [58]-[63].

In our model we interpret the observed annual amplitude as the reflection of the Earth´s gravitational radiation from the surface of the Sun (e.g. [64]) that leads to a small acceleration amplitude of the Earth on the path around the Sun. This scenario is given by (9) and (10):

$$a_{\oplus} = \frac{GM_{\oplus}}{\left(2*R_{perihelion}\right)^2} - \frac{GM_{\oplus}}{\left(2*R_{AU}\right)^2} \approx 1.53*10^{-10}\, ms^{-2} \tag{9}$$

$$a_{\oplus} = \frac{GM_{\oplus}}{\left(2*R_{aphelion}\right)^2} - \frac{GM_{\oplus}}{\left(2*R_{AU}\right)^2} \approx -1.44*10^{-10}\, ms^{-2} \tag{10}$$

In (9) and (10), the Earth is influenced by the self-gravitational effect via the reflection of the Earth´s gravitational radiation from the surface of the Sun: G is the Newtonian gravitational constant, $M_{\oplus}$ is the mass of the Earth, $R_{perihelion}$, R_{AU}, and $R_{aphelion}$ are distances between the Earth and the Sun.

In this model we interpret the observed diurnal amplitude as the result of Newton´s third law – for every action, there is an equal and opposite reaction between the Sun and the Earth. The Earth has acts daily with a slight change on the Sun with the gravitational force F_1 and the Sun is reciprocally acting on the Earth as is proposed by (11), (12), and (13):

$$a_{\odot\oplus} = \frac{GM_{\oplus}}{\left(R_{perihelion}-R_{\oplus}\right)^2} - \frac{GM_{\oplus}}{\left(R_{perihelion}+R_{\oplus}\right)^2} \approx 3.20*10^{-12}\, ms^{-2} \tag{11}$$

$$a_{\odot\oplus} = \frac{GM_{\oplus}}{\left(R_{AU}-R_{\oplus}\right)^2} - \frac{GM_{\oplus}}{\left(R_{AU}+R_{\oplus}\right)^2} \approx 3.04*10^{-12}\, ms^{-2} \tag{12}$$

$$a_{\odot\oplus} = \frac{GM_{\oplus}}{\left(R_{aphelion}-R_{\oplus}\right)^2} - \frac{GM_{\oplus}}{\left(R_{aphelion}+R_{\oplus}\right)^2} \approx 2.89*10^{-12}\, ms^{-2} \tag{13}$$

It will be interesting to re-analyze all data for the Pioneer 10/11 spacecrafts to obtain the annual and diurnal amplitudes for the given positions of the Earth around the Sun and to compare these quantities with the presented model.

VII. Conclusion

The deep study of the Pioneer anomaly can significantly contribute to our knowledge about gravitational events in the Solar System.

1. The Pioneer anomaly was interpreted as the action of the reflected Solar gravitational radiation from the Hydrogen wall on those spacecrafts.
2. The annual amplitude was interpreted as the reflection of the Earth´s gravitational radiation from the surface of the Sun – the Earth´s self-gravitational effect.
3. The diurnal amplitude was interpreted as the Third Newton´s law – action and reaction between the Earth and the Sun.
4. The dependence of the mass of the Pioneer 10/11 spacecrafts on temperature in the Solar System was derived. This tiny mass – temperature effect cannot be measured in the Earth´s laboratory at this epoch.
5. New missions of the Voyager type expeditions should be realized to get more detailed description of the Termination shock and the Hydrogen wall.
6. New missions of the Pioneer type expeditions should be realized to get more information about the Pioneer anomaly in the whole volume of the Solar System.

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CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

REFERENCES

[1] Anderson JD, Laing PA, Lau EL, Liu AS, Nieto MM, Turyshev SG. Indication, from Pioneer 10/11, Galileo, and Ulysses data, of an apparent anomalous, weak, long-range acceleration. *Phys. Rev. Lett*., 1998; 81: 2858-2861.
[2] Anderson JD, Laing PA, Lau EL, Liu AS, Nieto MM, Turyshev SG. Study of the anomalous acceleration of Pioneer 10 and 11. *Phys. Rev. D*. 2002; 65(8): 082004.
[3] Anderson JD, Laing PA, Lau EL, Nieto MM, Turyshev SG. The search for a standard explanation of the Pioneer anomaly. *Mod. Phys. Lett. A*. 2002; 17: 875-886.
[4] Anderson JD, Laing PA, Lau EL, Lin AS, Nieto MM, Turyshev SG. Study of the anomalous acceleration of Pioneer 10 and 11. 2004; *Arxiv*: gr-qc/0104064v5. Last access December 04 2022.
[5] Nieto MM, Turyshev SG.Finding the origin of the Pioneer anomaly. *Class. Quantum Grav*. 2004; 21: 4005-4023.
[6] Nieto MM, Anderson JD. Using early data to illuminate the Pioneer anomaly. *Class. Quantum Grav*. 2005; 22: 5343-5354.
[7] Turyshev SG, Nieto MM, Anderson JD. Study of the Pioneer anomaly: a problem set. *Am. J. Phys*. 2005; 73: 1033-1044.
[8] Turyshev SG, Toth VT, Kellogg LR, Lau EL, Lee KJ. The study of the Pioneer anomaly: new data and objectives for new investigation. *Int. J. Mod. Phys. D*. 2006; 15: 1-56.
[9] Turyshev SG, Nieto MM, Anderson JD. Lessons learned from the Pioneers 10/11 for a mission to test the Pioneer anomaly. *Adv. Space Res*. 2007; 39: 291-296.
[10] Nieto MM, Anderson JD. Search for a solution of the Pioneer anomaly. *Contemp. Physics*. 2007; 48: 41-54.
[11] Nieto MM. New Horizons and the onset of the Pioneer anomaly. *Phys. Lett. B*. 2008; 659: 483-485.
[12] Turyshev SG, Toth VT. The Pioneer anomaly. 2010; *Arxiv*: 1001.3686v2. Last access December 04, 2022
[13] Milgrom M. A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophys. J.* 1983; 270, 365-370.
[14] Foot R, Volkas RR. A mirror world explanation for the Pioneer spacecraft anomalies? *Phys. Lett. B*. 2001; 517: 13-17.
[15] Ostwang D. An explanation of the Pioneer effect based on quasi-metric relativity. *Class. Quantum Grav*. 2002; 19: 4131-4140.
[16] Rañada AF. The Pioneer riddle, the quantum vacuum and variation of the light velocity. *Europhys. Lett*. 2003; 63: 653-659.
[17] Mbelek JP. General relativity and quintessence explain the Pioneer anomaly. 2004; *Arxiv*: gr-qc/0407023.
[18] Moffat JW. Modified gravitational theory and the Pioneer 10 and 11 spacecraft anomalous acceleration. 2004; *Arxiv:* gr-qc/0405076. Last access December 04, 2022.
[19] Nieto MM, Turyshev SG, Anderson JD. Directly measured limit on the interplanetary matter density from Pioneer 10 and 11. *Physics Lett. B*. 2005; 613: 11-19.
[20] Jaekel MT, Reynaud S. Gravity tests in the Solar System and the Pioneer anomaly. *Mod. Phys. Lett. A*. 2005; 20: 1047-1055.
[21] Rañada AF. The Pioneer anomaly as acceleration of the clocks. *Found. Phys*. 2005; 34:1955-1971.
[22] De Diego JA, Núñez D, Zaval J. Pioneer anomaly? Gravitational pull due to the Kuiper belt. *Int. J. Mod. Phys. D*. 2006; 15: 533-544.
[23] Iorio L, Giuduce G. What do the orbital motions of the outer planets of the Solar System tell us about the Pioneer anomaly? *New Astronomy.* 2006; 11: 600-607.
[24] Page GL, Dixon DS, Wallin JF. Can minor planets be used to assess gravity in the outer Solar System? *Astrophys. J*. 2006; 642: 606-614.
[25] Bertolami O, Vieira P. Pioneer anomaly and the Kuiper belt mass distribution. 2006; *Arxiv*: astro-ph/0506330v3. Last access December 04, 2022.
[26] Reynaud S, Jaekel MT. Tests of general relativity in the Solar System. 2008; *Arxiv*: 0801.3407v1. Last access December 04, 2022.
[27] Tangen K. Could the Pioneer anomaly have a gravitational origin? *Phys. Rev. D.* 2007; 76: 042005.
[28] Iorio L. Can the Pioneer anomaly be of gravitational origin? A phenomenological answer. 2007; *Arxiv*: gr-qc/0610050v10. Last access December 04, 2022.
[29] Lachièze-Rez M. Cosmology in the Solar System: The Pioneer effect is not cosmological. *Class. Quantum Grav*. 2007; 24: 2735-2741.
[30] McCulloch ME. Modeling the Pioneer anomaly as modified inertia. *Mon. Not. R. Astron. Soc*. 2007; 376: 338-342.
[31] Oliveira FJ. Is the Pioneer anomaly a counter example to the dark matter hypothesis? 2007; *Arxiv*: gr-qc/0610029. Last access December 2022.
[32] Olsen Ø. The constancy of the Pioneer anomalous acceleration. Astron. Astrophys. 2007; 463: 393-397.
[33] Lämmerzahl C. The Pioneer anomaly or do we really understand the physics within the Solar System? 2008. https://www.zarm.uni-bremen.de/fileadmin/images/laemmerzahlDatei/Pioneer_Utrecht.pdf
[34] Siutsou IA, Tomilchik LM. On the gravitational origin of the Pioneer anomaly. 2008, *Arxiv*: 0908.1644v1. Last access December 04, 2022.
[35] Turyshev SG, Toth VT, Kinsella G, Lee SC, Lok S, Ellis J. Support for the thermal origin of the Pioneer anomaly. 2012; *Arxiv*: gr-qc/1204.2507v1. Last access December 04, 2022.
[36] Anderson JD, Morris JR. Brans-Dicke theory and the Pioneer anomaly. *Phys. Rev. D*. 2012; 86(6): 064023.
[37] Anderson JD, Morris JR. Chameleon effect and the Pioneer anomaly. *Phys. Rev. D*. 2012; 85(8): 084017.
[38] Gillies GT. The Newtonian gravitational constant: recent measurements and related studies. *Rep. Prog. Phys*. 1997; 60: 151-225.
[39] Gordin MD. *Einstein in Bohemia*. 2020; Princeton University Press, ISBN-10: 0691177376. pages: 25, 26, 39-42, 43, 74-75, 186, 225, 253.
[40] Těšínská E. *Albert Einstein and Gustav Jaumann on the balance (Negotiations for the professorship of theoretical physics at the German University in Prague in 1910-1911*. In Proceedings of the International Conference Cosmology on small scales 2022, Dark energy and the local Hubble expansion problem. Eds. Křížek M and Dumin YV., Prague, September 21-24, 2022: 145-168. https://css2022.math.cas.cz/proceedingsCSS2022.pdf.
[41] Einstein A. Die Grundlage der allgemeinen Relativitätstheorie. *Ann. Phys. (Lepzig).* 1916; 49: 769-822.

[42] Jaumann G. Theorie der Gravitation. Sitzungsberichte der Akademie der Wissenschaften in Wien, Mathematisch-Naturwissenschaftliche Klasse. *Abt. IIa*, 1912; 121: 95-182.
[43] Katushkina OA, Quémerais E, Izmodenov VV, Lallement R, Sandel BR. Voyager 1/UVS Lyman α measurements at the distant Heliosphere (90 – 130): unknown source of additional emission. *Journal of Geophysical Research*: Space Physics. 2017; 122: 10,921-10,937.
[44] Minter SJ, Wegter-McNelly K, Chiao RY. Do mirrors for gravitational waves exist? *Physica E: Low-dimensional systems and nanostructures.* 2010; 42(3): 234-255.
[45] Spherical cap. *Wikipedia*. Accessed December 02, 2022. https://en.wikipedia.org/wiki/Spherical_cap.
[46] Einstein A. Relativitätsprinzip und die aus denselben gezogenen Folgerungen. *Jahrbuch der Radioaktivität und Elektronik*. 1907; 4: 411-462.
[47] Assis AKT, Clemente RA. The influence of temperature on gravitation. *Il Nuovo Cimento Note Brevi*. 1993; (108B): 713-716.
[48] Martins RA. *Experimental studies on mass and gravitation in the early twentieth century: the search for non-Newtonian effects*. 2021; In Studies in History and Philosophy of Science, Quamcumque Editum. ISBN-10: 6599689019. pages 77-104. https://www.amazon.com/dp/6599689019.
[49] Martins RA. *The search for an influence of temperature on gravitation*. 2021; In Studies in History and Philosophy of Science, Quamcumque Editum. ISBN-10: 6599689019. pages 105-136. https://www.amazon.com/dp/6599689019.
[50] Thomson B. (Count Rumford). An inquiry concerning the weight ascribed to heat. *Philosophical Transactions of the Royal Society of London.* 1799; 89: 179-194.
[51] Poynting JH, Phillips P. An experiment with the balance to find if change of temperature has any effect upon weight. *Proceedings of the Royal Society of London.* 1905; (A 76): 445-457.
[52] Southerns L. Experimental investigation as to dependence of gravity on temperature. *Proceedings of the Royal Society of London* 1907; (A 78): 392-403.
[53] Pettersson H. Experiments with a new micro-balance. *Proceedings of the Physical Society of London*. 1919; 32: 209.
[54] Shaw PE, Davy N. The effect of temperature on gravitative attraction. *Physical Review*. 1923; 21: 680-691.
[55] Tajmar M, Plesescu F, Seifert B. Measuring the dependence of weight on temperature in the low-temperature regime using a magnetic suspension balance. *Meas. Sci. Technol*. 2010; 21: 015111.
[56] Tajmar M, Hentsch G, Hutsch T. Testing the influence of temperature on mass at high temperatures. *Measurements*. 2020; 172: 108917.
[57] Stávek J. Solar radiant heat reflected on the Termination shock might create excess microwave radiation in the horn antenna (Thermal telescope). *European Journal of Applied Physics.* 2022; 4(3) 38-42.
[58] Anderson JD, Laing PA, Lau EL, Liu AS, Nieto MM, Turyshev SG. Study of the anomalous acceleration of Pioneer 10 and 11. *Phys. Rev. D*. 2002; 65: 082004.
[59] Ghosh A. On the annual and diurnal variations of the anomalous acceleration of Pioneer 10. *Apeiron.* 2007; 14: 288-299.
[60] ten Boom PG. Reinterpreting the Pioneer anomaly and its annual residuals. 2008; *Arxiv*: gr-qc/0505077v2. Last access December 04, 2022.
[61] Levy A, Christophe B, Bério P, Métris G, Courty JM, Reynaud S. Pioneer Doppler data analysis: study of periodic anomalies. *Adv. Space Res*. 2009; 43: 1538-1544.
[62] Bilbao L, Bernal L. Minotti F. Vibrating Rays Theory. 2014; *Arxiv:* 1407.5001v12. Last access December 2022.
[63] Greaves ED, Bracho C, Gift S, Rodriguez AM. A solution to the Pioneer anomalous annual and diurnal residuals. *Progress in Physics.* 2021; 17(2): 168-184.
[64] Ignat´ev YG, Zakharov AV. The reflection of gravitational waves from compact stars*. Physics Letters A*. 1978; 66(1): 3-4.