Canadian Journal of Pure and Applied Sciences
Vol. 14, No. 1, pp. 4965-4974, Feb 2020
Online ISSN: 1920-3853; Print ISSN: 1715-9997
Available online at www.cjpas.net

PLANETARY DIVERGENCE EFFECT AND THE EVOLUTION OF SATURNIAN SYSTEM

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ABSTRACT

The paper introduces two new concepts for planetary and satellite systems: the equivalent energy orbit and the equivalent momentum orbit. It is proved that for circular orbits lying in the same plane, the equivalent energy orbit is always located below the equivalent momentum orbit. It is shown that due to energy losses caused by tidal friction, the equivalent energy orbit will gradually drop. Therefore, it is assumed that there is an effect of secular divergence of orbits that acts in planetary and satellite systems. We will term this effect as the Planetary divergence effect. A new hypothesis of the origin of Iapetus, Phoebe, Hyperion, and other external irregular satellites is proposed. The origin of the dichotomy and equatorial ridge of Iapetus, the origin of the dust ring of Phoebe and its retrograde orbit, the origin of Hyperion and its rapid proper rotation are explained. A new hypothesis of the formation of rings of Saturn and other giant planets is proposed. A series of experiments is proposed to comprehensively verify the planetary divergence effect.

Keywords: Planetary divergence effect, equivalent energy orbit, equivalent momentum orbit, dichotomy of Iapetus, Phoebe's ring, rotation of Hyperion, planetary rings, evolution of orbits.

INTRODUCTION

Iapetus is the outermost major satellite of Saturn. This is one of the most interesting objects of the Solar System. It has an unusual surface. The trailing hemisphere of Iapetus is approximately 10 times brighter than the leading hemisphere. The centers of the light and dark regions exactly coincide with the centers of the trailing and leading hemispheres. It is assumed that the bright region is the own surface of Iapetus, and the dark region is created by a dust cover several meters thick. This conclusion was drawn from observations of small craters on the dark side of the satellite (Denk *et al*., 2010).

It can be assumed that Iapetus moved through a dense cloud of dust and therefore its leading hemisphere is so dark. In 2009, a new ring was discovered around Saturn. This ring is a very rarefied giant cloud of dust visible only in infrared light. It begins beyond Iapetus' orbit and extends over millions of kilometers (Verbiscer *et al*., 2009). Any dusty formation in the Solar system cannot exist for a long time in its place because it quickly dissipates under the influence of the solar wind. Consequently, Saturn's giant dust ring has its own source of dust. It is assumed that the dust source is the moon of Saturn termed Phoebe that moves inside the ring in a retrograde orbit with a rather high eccentricity of 0.156.

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How did the Phoebe ring form? Some scientists believe that the Phoebe ring was formed as a result of the collision of Phoebe with a small asteroid or comet. But in this case, it is not clear why similar rings are not observed in other external satellites of the giant planets. There are other problems with the collision hypothesis. Suppose that several million years ago, Phoebe collided with a small body, and as a result, the fragments from the collision formed a ring. In this case, the small particles of the ring would disperse under the influence of the solar wind much faster than the large particles. Therefore, we could expect that the Phoebe ring consists mainly of large particles. However, the Phoebe ring consists mainly of dust particles ranging in size from 10 to 20 microns. Large stones measuring several tens of centimeters make up less than 10% (Hamilton *et al*., 2015). It can be assumed that dust particles and, possibly, larger objects regularly fly out from the surface of the Phoebe. Some scientists believe that the dust from the Phoebe's ring moves in a spiral towards Saturn and partially settles in the leading hemisphere of Iapetus (Cruikshank *et al*., 2014).

This is the most plausible explanation for the dichotomy of Iapetus. However, there is a problem with this assumption. If the dust migrated from the Phoebe ring and fell to Iapetus, then one would expect the following. In some regions of Iapetus dust would settle, and in some other regions it would not, and the border between these regions would not be sharp but gradual. However, this is not the case. The border between the light and dark areas is strongly torn and has a ragged appearance, where very light and very dark areas alternate. But at the same time, there are no smooth transitions between the dark and light areas of the surface. High resolution images show that the border between the light and dark areas is very sharp (Tamayo *et al*., 2010). This is possible if Iapetus moved through very dense clumps of dust.

Another interesting feature of Iapetus is its equatorial ridge with a length of 1,300 km that stretches along the equator. The width of the ridge is 20 km, the height reaches 13 km. Because of this ridge, Iapetus resembles a walnut. Some scientists suggest that this ridge is of exogenous origin. For example, Stickle and Roberts (2018) are exploring the possibility of a ridge forming from fallen objects that revolved around Iapetus. Other scientists suggest that the ridge is endogenous. For instance, Kuchta *et al.* (2015) develop a model that would explain the formation of the ridge as a result of cooling and deceleration of Iapetus own rotation.

An even more interesting feature of Iapetus is its orbit. At first glance, the orbit of Iapetus may seem pretty normal. This orbit is quite round and Iapetus moves along it in the forward direction. The retrograde orbit of Triton, the satellite of Neptune, looks more mysterious. Scientists are trying to explain the origin of Triton by capturing it from the heliocentric orbit. It is assumed that after the capture, its orbit was rounded off under the influence of tidal forces from Neptune. However, existing scenarios for the origin of Triton have problems. Some scenarios are reviewed in (Nogueira *et al*., 2011).

However, Iapetus' orbit is more mysterious than Triton's orbit. Iapetus orbits around Saturn with a radius of 3.5 million km (Table 1). Saturn's radius is 58.2 thousand km, so Iapetus is approximately 60 Saturn's radii from Saturn. The Moon is also removed from the Earth at 60 Earth radii.

It is now generally accepted that the Moon formed near the geostationary orbit and then moved a great distance away from the Earth due to the action of Earth's tides. But Iapetus could not move away from Saturn due to the action of the tides created by it on Saturn. Because in this case, Saturn would push away all the major internal satellites, which are many times closer to it than Iapetus. Maybe Iapetus formed in its orbit? It's impossible.

For a satellite to form as a result of accretion, it is necessary to have a plane, in which all particles and small bodies could gather before accretion starts. Such a plane is near the planet and coincides with the equatorial plane of the planet. Such a plane is far from the planet and coincides with the orbital plane of the planet. This plane is called a local Laplace plane or an invariable plane. When the satellite's orbit precessions, its angle of inclination remains constant relative to the local Laplace plane.

Near Titan's orbit, the local Laplace plane almost coincides with Saturn's equator. Near Phoebe's orbit, the local Laplace plane almost coincides with Saturn's orbit. At the same time, Saturn's equator is turned to its orbit at an angle of 27º. Thus, if we move along the influence zone of Iapetus, the local Laplace plane will gradually rotate by an angle of about 27º. Iapetus formed in the most unfortunate place. According to the accretion theory, the formation of Iapetus in its place is impossible due to the lack of a single plane for accretion. In addition, Iapetus' orbit is inclined at an angle of 8.3 degrees (table 1) that is an order of magnitude greater than that of regular satellites.

Consequently, Iapetus formed elsewhere and then migrated to the modern orbit. However, Iapetus is at a great distance from all the large bodies in the Saturn system. It is 3.5 million kilometers to Saturn, and it is more than two million kilometers to Titan, on the closest approaching (Table 1). What force could move Iapetus into the modern orbit? It is worth adding to this, that Iapetus' orbit is quite round. Its eccentricity is almost half the eccentricity of the Moon's orbit. There are only three logically possible options of the origin of Iapetus.

Option 1. Iapetus was formed outside Saturn's system and then was captured into Saturn's system.

Option 2. Iapetus was formed in Saturn's system as a result of joining small particles (accretion).

Table 1. The orbital and physical properties of the Saturnian big external satellites and the outermost satellite Fornjot. Data taken from NASA website: https://ssd.jpl.nasa.gov/?sat_elem#saturn and https://ssd.jpl.nasa.gov/?sat_phys_par

Satellite	Titan	Hyperion	Iapetus	Phoebe	Fornjot
Semi-Major Axis (10^3 km)	1222	1501	3561	12948	25146
Orbital Period (d)	15.95	21.28	79.33	550.31	1494.09
Eccentricity	0.0288	0.0274	0.0283	0.1635	0.2077
Inclination (deg.)	0.306	0.615	8.298	175.243	170.372
Mean radius(km)	2574.7	135	736	106.5	3.0
GM (km^3/s^2)	8978.14	0.373	120.5	0.553	–

Option 3. Iapetus was formed in Saturn's system as a result of the disintegration of a massive object (eruption).

Consider these three options.

1. Suppose Iapetus was captured. For this capture, it is necessary that Iapetus flight near a sufficiently massive object such as Titan. In this case, Iapetus would be captured in an elongated orbit with a pericenter inside Titan's orbit.

2. Suppose Iapetus formed in Saturn's system as a result of accretion. It could have been formed somewhere between its modern orbit and the orbit of Titan. In this case, Iapetus would have formed in a rather round orbit with a radius of about 2 million kilometers.

3. Suppose Iapetus formed in Saturn's system as a result of disintegration of a massive object. For example, Iapetus was erupted from Titan as a result of endogenous activity. In this case, Iapetus after the eruption would be in orbit crossing Titan's orbit.

We see that in all logically possible cases, the orbit of young Iapetus was much closer to Saturn than now. Thus, over several billion years, it has grown by at least 1.5 million kilometers. Due to the action of what forces did Iapetus' orbit grow? The tidal forces from Saturn are too weak at such vast distances. The only massive object is Titan. Could Titan push Iapetus 1.5 million kilometers? Next, we will try to answer this question.

The equivalent momentum orbit and the equivalent energy orbit

Consider two planets that move around the star in the same plane in close circular orbits. When moving in orbits of the planets, they periodically come closer to each other. The closer they are to each other, the stronger they interact with each other. Each planet enters the gravitational field of its neighbor and moves there along a ballistic trajectory. In this case, the planets exchange both energy and angular momentum. The orbital energy and angular momentum of each planet can change after such a maneuver.

In celestial mechanics, the size of the planets is usually neglected and planets are considered as point bodies. In this case, the total orbital energy of the planets and the total orbital angular momentum of the planets are strictly preserved and therefore do not change after their approach. But this is an approximate approach. In the case of extended bodies, such as planets, a tidal effect arises. When approaching, the planets stretch each other along the line connecting them. In this case, the crust, mantle, and core of each planet are deformed. With the removal of the planets, this deformation gradually disappears and all the energy spent on the deformation completely passes into heat. Where does this energy come from?

Part of this energy is taken from the rotation of the planets. When the planets approach, they slow down the rotation of each other in the same way as they slow down the rotation of their satellites. But even if the planets did not rotate, they would still lose some energy, spending it on compressing each other. In this case, part of the system energy is irreversibly converted into heat. It is clear that such a process will not work indefinitely. The source of energy will gradually decrease. The source of thermal energy is the orbital energy (kinetic and potential) of the planets in the star's gravitational field. That is, the orbits of the planets will gradually change. On the other hand, the total orbital angular momentum of the planets will be preserved because it does not go into heat. Therefore, if the radius of the orbit of one planet decreases, then in another it will increase. In this case, the radii of the planets must change so that the total orbital angular momentum of the planets remains unchanged.

In this case, two options are logically possible. In the first option, the radius of the orbit of the inner planet will increase and the radius of the orbit of the outer planet will decrease. In this case, the orbits of the planets will come closer together. In the second option, the radius of the orbit of the inner planet will decrease and the radius of the orbit of the outer planet will increase. In this case, the orbits of the planets will diverge.

Let two planets with masses m_1 and m_2 move in circular orbits with radii r_1 and r_2 around a star of mass M. Let us denote the orbital angular momentum of these planets by L_1 and L_2. The total orbital angular momentum of two planets is $L_0 = L_1 + L_2$. This value is strictly preserved during the interaction of the planets. If the orbits of the planets approach each other, then they will gradually approach a certain radius r_L, where the planets may unite into one body. If the orbits diverge, then extrapolating this divergence into the past, we get that once upon a time the planets could also be near the radius r_L. In both the scenarios there exists a certain radius r_L, on which the planets have an orbital angular momentum L_0. Let's find the radius r_L.

The orbital angular momentum L_1 is: $L_1 = m_1 r_1 V_1$. Here V_1 is the orbital velocity of the planet that is equal to: $V_1 = \sqrt{GM / r_1}$ (G is the gravitational constant). As a result, we get:

$$L_1 = \sqrt{GM}\; m_1 \sqrt{r_1} \tag{1}$$

The orbital angular momentum of the second planet is equal to:

$$L_2 = \sqrt{GM}\; m_2 \sqrt{r_2} \tag{2}$$

The total orbital angular momentum of two planets is equal to: $L_0 = L_1 + L_2 = \sqrt{GM}\,(m_1\sqrt{r_1} + m_2\sqrt{r_2})$. If the planets move in the same orbit of radius r_L, then their total orbital angular momentum will be equal to:

$$L_0 = \sqrt{GM}\,(m_1 + m_2)\sqrt{r_L} \tag{3}$$

As a result, we obtain: $(m_1 + m_2)\sqrt{r_L} = m_1\sqrt{r_1} + m_2\sqrt{r_2}$ resulting in

$$\sqrt{r_L} = \frac{m_1\sqrt{r_1} + m_2\sqrt{r_2}}{m_1 + m_2} \tag{4}$$

So, for two planets orbiting in the circular orbits r_1 and r_2, we found the radius of the orbit r_L, on which their total orbital angular momentum is equal to the sum of $L_1 + L_2$.

We introduced a new concept. We will call it the equivalent momentum orbit. Let us give it a general definition. Let there be N bodies that move in some orbits around a central body of mass M. The equivalent momentum orbit for these bodies will be called a circular orbit of radius r_L, which satisfies the following condition. If all N bodies are placed in this orbit, then their total orbital angular momentum L_0 will not change. Generalizing equation (3), we obtain:

$$\sqrt{r_L} = \frac{L_0}{\sqrt{GM}\cdot(m_1 + m_2 + ... + m_N)} \tag{5}$$

The orbital energy E_1 of a planet moving at speed V_1 in the circular orbit of radius r_1 is equal to the sum of its kinetic T_1 and potential U_1 energies: $E_1 = T_1 + U_1 = = \frac{m_1V_1^2}{2} - G\frac{Mm_1}{r_1}$. Given that $V_1 = \sqrt{GM/r_1}$, we obtain:

$$E_1 = -\frac{1}{2}G\frac{Mm_1}{r_1} \tag{6}$$

Thus, the total orbital energy of the planet has a negative sign and is equal to half its potential energy. Similarly, the total energy E_2 of the planet m_2 is equal to:

$$E_2 = -\frac{1}{2}G\frac{Mm_2}{r_2} \tag{7}$$

The total orbital energy E_0 for two planets is equal to the sum of their energies:

$$E_0 = -\frac{1}{2}GM\left(\frac{m_1}{r_1} + \frac{m_2}{r_2}\right) \tag{8}$$

The equivalent energy orbit for two planets will be called the circular orbit of radius r_E, which satisfies the following condition. If the planets are placed in this orbit, then their total energy will not change. The radius of the orbit r_E is determined by the following equation:

$$E_0 = -\frac{1}{2}G\frac{M}{r_E}(m_1 + m_2) \tag{9}$$

We introduced the definition of the equivalent energy orbit for two planets. This definition can be generalized. Suppose that there are N bodies: m_1, m_2, … m_N that move in some orbits around a central body of mass M. We will call the equivalent energy orbit for these bodies a circular orbit of radius r_E, which satisfies the following condition. If all N bodies are placed in this orbit, then their total orbital energy E_0 will not change. The radius of the orbit r_E is determined by the following equation:

$$E_0 = -\frac{1}{2}G\frac{M}{r_E}(m_1 + m_2 + ... + m_N) \tag{10}$$

Using equation (10), we find r_E:

$$r_E = -\frac{1}{2}G\frac{M}{E_0}(m_1 + m_2 + ... + m_N) \tag{11}$$

The equivalent energy orbit is below the equivalent momentum orbit

With the motion and gravitational interaction of bodies, their orbits can change. However, the total orbital angular momentum will be strictly preserved. Therefore, the orbit of the total angular momentum will remain constant. Since all bodies (planets, satellites, asteroids, etc.) have dimensions, when approaching, they deform each other with their gravitational fields. The energy spent on deformation is irreversibly converted into heat. Therefore, over long periods of time, the total orbital energy of bodies E_0 decreases. Consequently, the orbit radius of the total energy r_E (11) gradually decreases. What will the result of this?

If the equivalent energy orbit is located above the equivalent momentum orbit, then during the interaction of the planets this orbit will gradually go down, and the orbits will come closer together. When the equivalent energy orbit goes down to the equivalent momentum orbit, the orbits of the planets will fully converge. If the equivalent energy orbit is located below the equivalent momentum orbit, then when the planets interact, this orbit, gradually dropping, will be further and further removed from the orbit of the equivalent momentum orbit. In this case, the orbits of the planets will diverge.

First, we analyze the simplest case of two planets with the same mass $m_1 = m_2$. From formula (4), we find the radius of the orbit of the total angular momentum r_L:

$$\sqrt{r_L} = \frac{\sqrt{r_1} + \sqrt{r_2}}{2} \tag{12}$$

Square this expression:

$$r_L = \frac{r_1 + r_2 + 2\sqrt{r_1 r_2}}{4} = \frac{\frac{r_1 + r_2}{2} + \sqrt{r_1 r_2}}{2} \qquad (13)$$

Now we find where the orbit of total energy r_E is located for two planets. Given equation (9), we obtain:

$$E_0 = -\frac{1}{2}GM\left(\frac{m_1}{r_1} + \frac{m_2}{r_2}\right) = -\frac{1}{2}G\frac{M}{r_E}(m_1 + m_2) \qquad (14)$$

After reduction: $\frac{m_1}{r_1} + \frac{m_2}{r_2} = \frac{m_1 + m_2}{r_E}$. If $m_1 = m_2$, then:

$$\frac{1}{r_1} + \frac{1}{r_2} = \frac{2}{r_E} \qquad (15)$$

We transform this expression to a form in which there is only the arithmetic mean and geometric mean: $\frac{r_E}{2} = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2}} = \frac{1}{\frac{r_2 + r_1}{r_1 r_2}} = \frac{r_1 r_2}{r_1 + r_2}$ resulting in

$$r_E = \frac{r_1 r_2}{\frac{r_1 + r_2}{2}} = \frac{\sqrt{r_1 r_2}\sqrt{r_1 r_2}}{\frac{r_1 + r_2}{2}} \qquad (16)$$

Let us compare the quantities (13) and (16), given that the arithmetic mean is greater than the geometric mean. The radius r_L (13) of the equivalent momentum orbit is the arithmetic mean between the arithmetic mean of two orbits $\frac{r_1 + r_2}{2}$ and the geometric mean of the same orbits $\sqrt{r_1 r_2}$. Therefore, r_E is greater than the geometric mean $\sqrt{r_1 r_2}$. The radius r_E (16) of the orbit of the total energy is the geometric mean multiplied by the ratio of the geometric mean to the arithmetic mean. Therefore, r_E is less than the geometric mean $\sqrt{r_1 r_2}$. Consequently:

$$r_L > r_E \qquad (17)$$

Thus, for two planets of the same mass lying in the same plane and moving in circular orbits, the radius of the equivalent energy orbit r_E is below the radius of the equivalent momentum orbit r_L. Suppose r_1 = 1 a.u. (astronomical unit), r_2 = 2 a.u. Substituting these numbers in equations (13) and (16), we obtain: $r_L \approx 1.46$, $r_E \approx 1.33$. In this case, the equivalent energy orbit is located approximately 10 percent below the equivalent momentum orbit.

So, the radius of the equivalent energy orbit for two identical planets moving in the same plane in circular orbits is located below the radius of the equivalent momentum orbit. Due to the tidal interaction, the orbital energy of the planets gradually turns into heat. Therefore, the equivalent energy orbit also gradually drops and goes further away from the equivalent momentum orbit. Consequently, the orbits of the planets diverge. Each time, being nearby, the planets will repel each other a little. The radius of the orbit of the inner planet will gradually decrease, and the radius of the orbit of the outer planet will increase. Therefore, there must be an effect of secular divergence of planetary orbits. We derived this effect assuming that masses of the planets are equal. However, it is intuitively obvious that it is also true for planets of different masses. Let's figure this.

The Planetary Divergence Effect

Suppose two bodies m_1 and m_2 move at velocities V_1 and V_2 in the same plane in circular orbits with radii r_1 and r_2 around a large mass M. The kinetic energies T_1 and T_2 of these bodies are equal to: $T_1 = \frac{m_1 V_1^2}{2}$ and $T_2 = \frac{m_2 V_2^2}{2}$.

After the interaction, the kinetic energies of the bodies can change:

$$dT_1 = m_1 V_1 dV_1 \qquad (18)$$

$$dT_2 = m_2 V_2 dV_2 \qquad (19)$$

The orbital angular momenta L_1 and L_2 of the bodies are equal to: $L_1 = m_1 r_1 V_1$ and $L_2 = m_2 r_2 V_2$. During the interaction of bodies, the angular momentum and energy are exchanged. In this case, the total orbital angular momentum L_0 is preserved:

$$dL_0 = m_1 r_1 dV_1 + m_2 r_2 dV_2 \qquad (20)$$

Express dV_2 through dV_1:

$$dV_2 = -\frac{m_1 r_1}{m_2 r_2} dV_1 \qquad (21)$$

Substitute this expression into formula (19) and get:

$$dT_2 = m_2 V_2 \left(-\frac{m_1 r_1}{m_2 r_2}\right) dV_1 = -\frac{m_1 r_1 V_2}{r_2} dV_1 \qquad (22)$$

According to equation (18), $dV_1 = \frac{dT_1}{m_1 V_1}$. Substitute this value in equation (22):

$$dT_2 = -\frac{m_1 r_1 V_2}{r_2}\frac{dT_1}{m_1 V_1} = -\frac{r_1 V_2}{r_2 V_1} dT_1 \qquad (23)$$

The angular velocities ω_1 and ω_2 at which the bodies move along the orbits r_1 and r_2 are equal to: $\omega_1 = V_1/r_1$ and $\omega_2 = V_2/r_2$. Substituting these values in equation (23), we obtain:

$$dT_2 = -\frac{\omega_2}{\omega_1} dT_1 \qquad (24)$$

Find the complete change in the kinetic energy dT_0 for two bodies:

$$dT_0 = dT_1 - \frac{\omega_2}{\omega_1} dT_1 = dT_1(1 - \frac{\omega_2}{\omega_1}) \qquad (25)$$

The kinetic energy of bodies gradually decreases as it gradually turns into heat. We write this as inequality:

$$dT_0 = dT_1(1 - \frac{\omega_2}{\omega_1}) < 0 \qquad (26)$$

Since $\omega_1 > \omega_2$, then $(1 - \frac{\omega_2}{\omega_1}) > 0$, therefore, $dT_1 < 0$. Thus, the kinetic energy of the first body T_1 will decrease and therefore, the kinetic energy of the second body T_2 will increase.

So, we found out that when two bodies move in orbits, kinetic energy is transferred from the inner body to the outer body. Energy is transferred from the body with a higher angular velocity of motion to the body with a lower angular velocity of motion. Only in this case, the total orbital energy of two bodies will decrease. The reverse process is impossible because it requires an additional energy.

A similar result was obtained for the transfer of energy from a planet to a satellite as a result of tidal friction. A planet can transmit energy to a satellite only if its angular velocity of rotation around its axis is higher than the angular velocity of the satellite in orbit (Darwin, 1898). If the angular velocity of the satellite in orbit is higher than the angular velocity of rotation of the planet, then the energy is transmitted from satellite to planet, and the satellite slowly falls to the planet (Burns, 1986). The formula for the tidal friction efficiency is given in (Yanchilin, 2018).

The process of transferring energy from an internal planet to an external planet resembles the process of transferring energy from a rapidly rotating planet to its satellite. The tidal bulge created by the Moon on the surface of the Earth moves faster than the Moon and as a result accelerates the Moon (MacDonald, 1964). Some planet, such as Venus, can be compared with a kind of tidal bulge extended one hundred million kilometers from the Sun. This bulge moves faster than the Earth and accelerates the movement of the Earth. As a result, the orbits of Venus and Earth gradually diverge.

From the analysis of all available radiometric measurements between the Earth and planets, including observations of Martian ships and orbiting apparatuses for 1971–2003, Krasinsky and Brumberg (2004) made the following conclusion. The astronomical unit increases by 15±4 m/year. Krasinsky and Brumberg (2004) also concluded that there is currently no explanation for this effect. It is possible that the Earth's removal from the Sun is caused by the planetary divergence effect.

Experimental verification of the planetary divergence effect

Now Iapetus, the satellite of Saturn, is moving in an orbit in which it could not be formed according any known theory. We investigated the possible ways of its getting it into the modern orbit and concluded that Iapetus' orbit grew by 1.5 million kilometers, if it formed as a result of accretion. Another option: the pericenter of Iapetus' orbit has moved away from Saturn by at least 2.3 million kilometers, if Iapetus was captured in the Saturnian system or, conversely, is erupted from Titan.

If Iapetus' orbit has grown due to the effect of planetary divergence, then it will continue to grow and this growth can be measured. Suppose Iapetus had formed 4.5 billion years ago as a result of accretion in orbit with a radius of about 2 million kilometers. In this case, the average growth rate of its orbit is $V_I = 1.5 \cdot \times 10^9$ m/$4.5 \cdot \times 10^9$ years = 0.33 m/year. This is almost 10 times more than the current growth rate of the lunar orbit that is 3.8 cm/year. The current growth rate of the lunar orbit is lower than its average speed by about 2 times if the Moon formed 4.5 billion years ago. We can conclude that the current growth rate of Iapetus' orbit is about 15 cm/year, if it was formed as a result of accretion happened 4.5 billion years ago. However, if Iapetus was thrown out of Titan, then its modern orbit growth rate can reach 30 cm/year and even more, depending on the time of its ejection.

An experiment to measure the growth rate of Iapetus' orbit is quite feasible in the near future. If it is confirmed that Iapetus actually is moving away from Saturn at a speed of the order of 10-15 cm/year, then this will be direct experimental confirmation of the planetary divergence effect. In addition, if it turns out that Iapetus' orbit is growing at a speed of 30 cm/year or more, then we can conclude the following. The age of Iapetus is much younger than 4.5 billion years, and it could not be formed as a result of accretion. In this case, we can assume that Iapetus was thrown out of Titan. The ejection time of Iapetus can be estimated by the growth rate of its orbit.

Hypothesis about the origin of Iapetus and its equatorial ridge

Given the above about the divergence of satellite orbits, we put forward the following hypothesis about the origin of Iapetus. From 2 to 4 billion years ago, Iapetus was erupted from the young and very active Titan. A more accurate estimate of the eruption time can be made after an experiment to measure the growth rate of Iapetus' orbit. The escape speed from the surface of Titan is 2.6 km/s. Consequently, the speed of the erupted Iapetus exceeded this speed. Having received such a high speed during the eruption, Iapetus had to get a high speed of rotation. We can conclude that the young Iapetus rotated around its axis at a speed close to the speed of rotational instability. Under the planetary divergence effect, Iapetus quickly enough moved away from Titan.

As the reader knows, all the large moons of Saturn are always turned towards it with the same hemispheres. This is a consequence of the fact that Saturn with its tidal forces slowed down the rotation of its moons. Iapetus is also turned towards Saturn with the same hemisphere. However, Iapetus is situated much further from Saturn than other large moons. In addition, tidal forces decrease in proportion to the cube of distance. Therefore, we can conclude that Saturn inhibited the rotation of Iapetus much later than the rotation of the closer moons. Indeed, this is true. As a result of the study of Iapetus from the Cassini spacecraft, the following conclusion was made. The bowels of Iapetus hardened when it rotated very quickly, making one revolution around its axis in 17 hours (Jaumann*et al*., 2009). That is, Saturn braked the rotation of Iapetus after the bowels of Iapetus cooled down. We can conclude that the young Iapetus rotated around its axis at a higher speed, possibly at a speed close to the rotational instability. This is consistent with the assumption of its eruption at high speed from the bowels of Titan. Consider the conclusions that follow from this assumption.

Young Iapetus rotated around its axis on the verge of rotational instability. In addition, it was quite warmed up, as it was erupted from the bowels of active Titan. Therefore, the shape of Iapetus represented an ellipsoid of revolution with a significant thickening along the equator. When the crust (outer shell) of Iapetus cooled and hardened, the inner part of Iapetus was still quite hot. Over time, Iapetus slowed down due to tidal friction. The outer hardened part of Iapetus retained its shape. The inner partly molten part gradually took the form of a ball. As a result, its surface area gradually decreased. An empty space appeared along the equator between the inner part and the outer crust. The heavier half of the crust descended on the inner part of Iapetus and, possibly, partially plunged into it. Accordingly, the opposite part of the crust, on the contrary, rose above the inner part along the equator. As the inner part of Iapetus slowed down and contracted along the equator, the heavier half of the crust remained lying on the inner part, slowly descending with it. Accordingly, the opposite half of the crust slowly rose above the inner part of Iapetus along the equator. When this part of the crust rose high above the equator, it collapsed under its own weight. As a result, an equatorial mountain range with a length of 1300 kilometers was formed. This is slightly less than half the length of the equator in Iapetus. Scientists associated with the Cassini mission also believe that the Equatorial ridge on Iapetus could be a remnant of the ellipsoidal shape of young Iapetus when it spun faster than today (Kerr, 2006).

Hypothesis on the origin of Phoebe and the dichotomy of Iapetus

Titan is 75 times heavier than Iapetus (Table 1), almost as much as the Earth is heavier than the Moon. The hypothesis of the eruption of the Moon from the Earth is considered in (Yanchilin, 2019). Iapetus is one of Saturn's largest moons, after Titan. Iapetus is only slightly lighter than Rhea. If the young Titan possessed sufficient endogenous activity for the eruption of Iapetus, then it is quite possible that the remaining ice moons of Saturn were erupted from Titan. In addition, in this case, one would expect a large number of small moons, also erupted from Titan. Where are they?

We can assume that one part of these small moons was thrown out of the Saturn system having formed part of the family of comets and centaurs. The second part may have been pushed by large moons into the Saturn system up to the Roche limit. Inside the Roche limit, the small moons were torn apart by the tidal forces of Saturn and formed many ice rings. And finally, the third part of the small moons erupted from Titan was pushed to the periphery of the Saturn system, having formed two groups of irregular satellites with prograde and retrograde motion.

The semi-major axes of the orbits of the most distant satellites of Saturn are about 2 times larger than the semi-major axis of Phoebe's orbit (Table 1). We assume that all small moons move to the periphery of the Saturn system at approximately the same speed, which decreases as they move away. This means that Phoebe's age is at least 5-6 times smaller than the age of the most distant moons. That is, Phoebe is a young object in the Saturnian system. Its age is less than a billion years. However, perhaps Phoebe's age is about 200-400 million years. A more accurate estimate of Phoebe's age can be made after an experiment to measure the growth rate of its orbit.

We have already noted that Phoebe moves inside a giant dust ring, which also contains objects a few centimeters in size. Obviously, this ring consists of a substance erupted from Phoebe. That is, Phoebe shows endogenous activity. At such a small facility, endogenous activity cannot last billions of years. Therefore, we can conclude that Phoebe is a young object whose age is several hundred million years. This is the conclusion we made on the basis of the planetary divergence effect. The most important thing here is that we can verify this extraordinary conclusion in an experiment measuring the growth rate of Phoebe's orbit.

Thus, Phoebe was erupted from Titan much later than Iapetus. By this time, Saturn had completely braked the rotation of Iapetus, and only one Iapetus' hemisphere faced Saturn, like the Moon faces Earth. In contrast to Iapetus, Phoebe was erupted into retrograde orbit. It is quite possible that Phoebe's orbit initially had a high eccentricity and was crossing Iapetus' orbit. After several rapprochements with Iapetus, Phoebe was transferred by Iapetus to a higher orbit. At that time, Phoebe was much younger and more active than now. Therefore, dark matter was erupting from Phoebe's surface in more significant quantities. Dark matter from Phoebe was dropping mainly on the leading Iapetus' hemisphere. As a result, the leading Iapetus' hemisphere became dark, and the driven hemisphere remained mostly light. So, the modern dichotomy of Iapetus was formed. Then, due to the planetary divergence effect, Phoebe gradually retired to the modern orbit.

Origin of Hyperion

Saturn has a satellite with a very strange orbit. This is Hyperion. Its orbit is located very close to Titan's orbit (table 1). How did Hyperion get into its orbit? Could it form in its orbit 4.5 billion years ago as a result of accretion? This is only possible if two assumptions are made. Assumption 1: small bodies can form in orbits that are very close to the orbits of large bodies. Assumption 2: the orbits of small bodies near large bodies are stable for billions of years. First, both of these assumptions are too implausible. Second, if we do them, then the following questions will immediately arise. Why are there no orbits of small moons near other large satellites? Why is Hyperion so unique?

From a new point of view there is only one explanation for the strange orbit of Hyperion. This orbit is unstable, as it is located close to the orbit of a massive satellite. According to the planetary divergence effect, Hyperion should quickly move away from Titan. Therefore, Hyperion is a very young object. It is several times younger than Phoebe and its age is about 100 million years. Is there evidence of Hyperion's youth? Yes, this is its own rapid rotation. High-resolution Voyager images and an analysis of the light curve show that Hyperion spins around its axis with a period close to 13 days (Thomas *et al*., 1984; Thomas and Veverka, 1985). A similar value of the period was derived from ground-based photometric observations in (Morrison *et al*., 1986). At the same time, it moves in orbit with a period of 21 days. That is, the tidal forces from the side of Saturn did not manage to slow down Hyperion's own rotation.

Some scientists expected Hyperion to rotate synchronously. In the famous monograph *Planetary Satellites* of the University of Arizona Publishing House, Hyperion's own rotation was discussed. Peel (1977) argued that Hyperion must rotate synchronously because it is significantly closer to Saturn than Iapetus, which rotates synchronously. Why is Hyperion not spinning synchronously? It is because Saturn did not have time to slow down Hyperion's rotation to some synchronous state. Why did Saturn brake Iapetus located farther and did not manage to brake Hyperion? The simplest explanation is that Hyperion is a young object. How can this be checked? It is necessary to conduct an experiment to measure the growth rate of Hyperion's orbit.

If Hyperion's age is about 1 billion years, then the average growth rate of the semi-major axis of its orbit is approximately 280 thousand km/10^9 = 28 cm/year. Accordingly, the current growth rate of the semi-major axis of the orbit is about 2 times less and amounts to 10-15 cm/year. If Hyperion's age is about 100 million years, then the modern growth rate of its orbit is ~ 1 m/year. If we conduct an experiment to measure the growth rate of the semi-major axis of Hyperion's orbit, we can not only confirm (or disprove) the existence of the planetary divergence effect but also determine Hyperion's age.

CONCLUSION

We introduced two new concepts: the equivalent energy orbit and the equivalent momentum orbit. These orbits are determined by the following conditions. If some satellites (or planets) are placed in the equivalent energy orbit, then their total gravitational energy will remain the same. If the same satellites are placed in the equivalent momentum, then their total orbital momentum will remain the same. These conditions can be written in the form of equations (11) and (5).

Then we proved that for circular orbits lying in the same plane, the equivalent energy orbit is always located below the equivalent momentum orbit. At first, we proved this for two objects of equal mass. Then we proved this for planets (moons) with arbitrary masses. This fact is important for the evolution of planetary systems. When planets (satellites) come together, they deform each other with tidal forces and therefore part of the orbital energy goes into heat. As a result, the equivalent energy orbit gradually drops. In this case, the equivalent momentum orbit remains in the same place. As a result, the orbits of the planets (satellites) diverge. This means that there is an effect of divergence of orbits. We called this effect the planetary divergence effect, implying that any planetary system, including its satellite subsystems, will gradually expand. In this case, the orbital energy will be transmitted from the inner planets (satellites) to the outer planets (satellites). This effect is similar to the effect of tidal friction, when energy is transferred from the planet to its satellites.

We do not know the magnitude of the planetary divergence effect. Perhaps this effect is small and does not play any significant role in the evolution of planetary (satellite) orbits. However, perhaps, the planetary

divergence effect is quite large and plays a decisive role in the evolution of planetary and satellite orbits. To find out the role of the planetary divergence effect, we examined Iapetus, the satellite of Saturn.
As it turned out, Iapetus could not form in its place as a result of accretion. Therefore, we considered all three possible options for its formation. This is accretion near Titan, the capture in the Saturnian system after rapprochement with Titan and the eruption from Titan. In all these three cases, the orbit of the young Iapetus was much closer to Saturn than it is now. To explain the modern orbit of Iapetus, we suggested that it grew under the influence of the planetary divergence effect. This assumption can be verified experimentally. If Iapetus really moved away from Saturn under the influence of the planetary divergence effect, then its orbit should continue to grow at a speed of about 15 cm/year. By measuring the growth rate of Iapetus' orbit, we can find out whether the planetary divergence effect is true or not and what role this effect plays in the evolution of orbits.

Having examined the location of the Hyperion orbit that is very close to Titan's orbit, we came to the conclusion that this orbit is unstable. Based on the planetary divergence effect, we concluded that Hyperion should quickly move away from Titan. By experimentally measuring the growth rate of Hyperion's orbit, we can also verify the correctness of the planetary divergence effect. In addition, knowing the magnitude of the growth rate of Hyperion's orbit, we can estimate the time when this satellite of Saturn was erupted from Titan. If it is established that the growth rate of Hyperion's orbit is ~ 1 m/year, as the author suggests, then Hyperion was erupted approximately 100 million years ago. In this case, it becomes clear why Hyperion spins around its axis faster than it orbits around Saturn. Saturn has not yet had time to slow down spinning Hyperion to the synchronous state. Hyperion's orbital period is 21 days and its own spinning period is 13 days.

According to the planetary divergence effect, large satellites of giant planets should move small internal satellites away from themselves. As a result, small internal satellites are gradually approaching their planets and, reaching the Roche limit, are torn to pieces by tidal forces. The author believes that rings of the gigantic planets are formed in this way. From this point of view, the rings are fairly young formations with an age of the order of Hyperion's age, that is 100-200 million years. The substance of Saturn's rings is constantly dropping on Saturn but in return new rings appear due to the destruction of new small moons. A new hypothesis of rings formation can also be verified experimentally. To do this, we need to measure the speed, at which the orbits of the small internal satellites of the gigantic planets are reduced.

The author also wants to attract the attention of astronomers to the discovery of the planetary divergence effect. If it is experimentally established that this effect plays a significant role in the evolution of orbits, then this will change our ideas about the origin of satellites, planetary rings, and other bodies of the Solar system.

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Received: Jan 6, 2020; Accepted: Feb 1, 2020

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