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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ**

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

**НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
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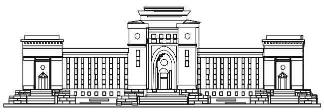

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ON THE EXISTENCE OF TWO CLASSES OF CIRCULAR ORBITS OF THE TEST BODY IN HILL VARIABLES

Abstract. The work [1, p. 119] of B. M. Schigolev investigated the second plane problem of Hill. For it, Hill proposed a scheme of the power function

$$U=\frac{\mu}{r}+\frac{1}{2}\nu r^2,\quad r^2=x^2+y^2,\ \nu>0,\quad \mu=f(m_0+m),$$

where m_0 – central body mass; m – test body mass; f – the gravitational constant.

The structure of the force function is motivated by the fact that the motion of the pericenter (and the node in the spatial problem) is taken into account in the plane problem.

B.M. Schigolev avoiding the well known idea of circular orbits in the Hill second task, using his original method, has found [1, p. 98] following existence and evolution of circular orbits of the test body:

1. When $\alpha<0{,}10546875$ there are two circular orbits.
2. These orbits are merged into one at $\alpha=0{,}10546875$.
3. They disappear when $\alpha>0{,}10546875$.

In this paper we prove the validity of these conclusions and in the case of the Hill plane problem. The existence of two classes of circular orbits in Hill variables is determined. The boundaries of these classes have been found as in Hill variables so in present variables. It was found laws valid both in flat and in case of a small inclination of the orbit to the main plane.

Key words: test body, of circular orbits, the Hill variables, class of orbits, Hill gravitational field, Earth satellite.

The differential equations of the orbital motion of the test body in the Hill variables have the form [1, p. 93]:

$$\left.\begin{aligned}&\frac{d^2w}{d\upsilon^2}+\left(1+\frac{\alpha}{w^4}\right)w-\frac{1}{(1+s^2)^{3/2}}=0,\\&\frac{d^2s}{d\upsilon^2}+\left(1+\frac{\beta}{w^4}\right)s=0,\end{aligned}\right\}\qquad(1)$$

where the variables w, s and Hill constants α, β – dimensionless, ϑ – the true length of the test body. They are defined by formulas

$$w=\frac{C^2}{\mu}\cdot\frac{1}{\rho},\quad s=\operatorname{tg}\varphi,\quad \alpha=\frac{\nu C^6}{\mu^4},\quad \beta=\frac{(\nu-\nu')C^6}{\mu^4},\qquad(2)$$

where C – area integral constant, $\rho^2=x^2+y^2$ – the projection of the radius-vector of the test body onto the Oxy plane, s – latitude tangent, φ – latitude of the test body, ν and ν′ – Parameters chosen so that there will be actual observed motions of the pericenter and the node of the orbit.

True longitude and time are related to each other by the differential equation

$$\frac{d\vartheta}{dt}=\frac{C}{\rho^2}. \tag{3}$$

Expanding $\frac{1}{(1+s^2)^{3/2}}$ in a binomial series in powers of s, we can see that (1) describes the motion of the test body quite adequate at $0\le\varphi\le 10^0$.

The first-approximation equations at $s\neq 0$, $s^2\approx 0$ have the form:

$$\left.\begin{aligned}&\frac{d^2w}{d\upsilon^2}+\left(1+\frac{\alpha}{w^4}\right)w-1=0,\\&\frac{d^2s}{d\upsilon^2}+\left(1+\frac{\beta}{w^4}\right)s=0.\end{aligned}\right\} \tag{4}$$

The first equation from (4) at $w=R=\text{const}$ transforms into the equation of circular orbits

$$w^4-w^3+\alpha=0, \tag{5}$$

because $\frac{d^2w}{d\upsilon^2}=0$ and $w\neq 0$.

The same equation from (4) allows a decrease in the order [1, c. 99]:

$$d\vartheta=\frac{wdw}{\sqrt{\alpha+Hw^2+2w^3-w^4}}, \tag{6}$$

where $H=\frac{2hC^2}{\mu^2}$, h – energy integral constant.

In the case of the circular motion type $\alpha>0$, $H<0$, $e=0$, therefore (6) will have the form [2, p. 79]:

$$d\vartheta=\frac{wdw}{\sqrt{\alpha-Hw^2+2w^3-w^4}}, \tag{7}$$

e – eccentricity of the orbit.

Polynominal

$$P(w)=-w^4+2w^3-Hw^2+\alpha$$

has three positive roots α_1, α_2, α_3 and one negative root α_4, and let it be

$$\alpha_1>\alpha_2>\alpha_3>\alpha_4.$$

The actual motions correspond to positive values of the polynomial, $P(w)$, which are realized on two intervals [2, p. 79]:

A) $\alpha_4<w<\alpha_3$; B) $\alpha_2<w<\alpha_1$.

Let us consider the second interval $\alpha_2<w<\alpha_1$. After the transition to the Legendre normal form, we have [2, p. 82]:

$$d\vartheta=\mu_0\frac{wd\psi}{\sqrt{1-k^2\sin^2\psi}},\quad 0\le\psi\le\frac{\pi}{2}, \tag{8}$$

where

$$w=\frac{\alpha_2\alpha_{31}-\alpha_3\alpha_{21}\sin^2\psi}{\alpha_{31}-\alpha_{21}\sin^2\psi}, \tag{9}$$

$$k^2=\frac{\alpha_{43}\alpha_{21}}{\alpha_{31}\alpha_{42}},\quad \mu_0=\frac{2}{\sqrt{\alpha_{31}\alpha_{42}}},\quad 0<k<1,\quad \alpha_{ik}=\alpha_k-\alpha_i\quad (k,i=1,2,3,4).$$

The first circular orbit is apparently realized when $\psi = 0$, here from (8) and (9) we have

$$R_1 = w_1 = \alpha_2 . \tag{10}$$

The second circular orbit is apparently realized when $\psi = \frac{\pi}{2}$, here from (8) and (9) we have

$$R_2 = w_2 = \alpha_1 .$$

Except that $R_2 > R_1$. On the Oxy plane they are arranged concentrically.

On the interval $\alpha_4 < w < \alpha_3$ similarly we have two more circular orbits

$$R_3 = w_3 = \alpha_4 \text{ at } \psi = 0 \text{ and } R_4 = w_4 = \alpha_3 \text{ at } \psi = \frac{\pi}{2} .$$

By combining the center of the circles with the center mass of the central body, we have 4 circular concentric orbits (figure 1). Radii of circular orbits as rising ψ from 0 to $\frac{\pi}{2}$, increase from R_3 to R_4 and from R_1 to R_2. There is no actual motion between the roots (α_3, α_2), as there is the polinomial $P(w) < 0$. It should be noted that the actual motions of the test body exist on the intervals (α_2, α_1) and (α_4, α_3), as they have $P(w) > 0$.

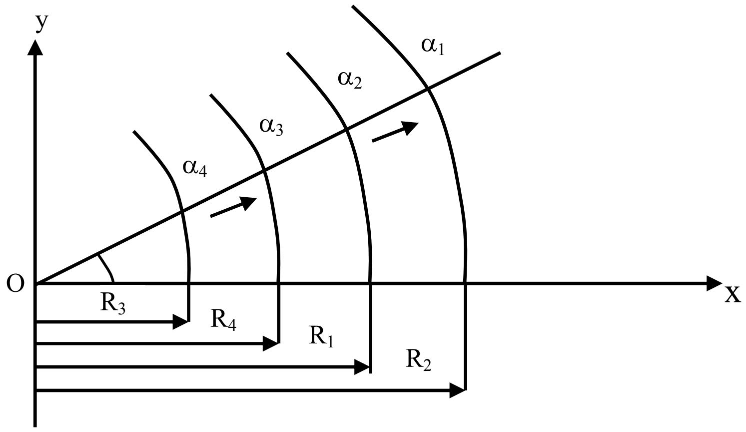

Figure 1 – The boundaries of circular orbits in Hill variables

Evolution of circular orbits on the segment [α_2, α_1] can be traced by the equation [2, p. 82]

$$w = (w_{00} + w_{02}k^2) + (w_{12}k^2 + w_{14}k^4)\cos 2\psi + w_{24}k^4 \cos 4\psi , \tag{11}$$

where

$$w_{00} = \alpha_2, \; w_{02} = \frac{\alpha_{21}\alpha_{32}}{\alpha_{31}} + \frac{3}{8}\frac{\alpha_{42}^2\alpha_{32}}{\alpha_{43}}, \; w_{12} = -\frac{\alpha_{42}\alpha_{32}}{2\alpha_{43}}, \; w_{14} = -\frac{\alpha_{32}\alpha_{42}^2}{2\alpha_{43}^2}, \; w_{24} = -\frac{1}{4}w_{14} .$$

It follows from (11) that, as ψ increases from 0 to $\frac{\pi}{2}$ the radii of circular orbits grow continuously from R_1 to R_2. Between them there is a whole class of circular orbits. Let us call them the I-class of circular orbits. Evolution of circular orbits on the segment [α_4, α_3] can be traced by the equation [2, p. 80]:

$$w = (w_{00} + w_{02}k^2) + (w_{12}k^2 + w_{14}k^4)\cos 2\psi + w_{24}k^4 \cos 4\psi , \tag{12}$$

where

$$w_{00} = \alpha_3, \; w_{02} = -\frac{\alpha_{31}^2\alpha_{42}}{2\alpha_{41}\alpha_{21}}, \; w_{12} = w_{02}, \; w_{14} = -\frac{1}{2}\alpha_{31}^2\left(\frac{\alpha_{42}}{\alpha_{41}\alpha_{21}}\right)^2, \; w_{24} = -\frac{1}{8}\alpha_{31}^2\left(\frac{\alpha_{42}}{\alpha_{41}\alpha_{21}}\right)^2 .$$

The (12) series stops at k^4 with an error in order $O(k^5)$. With growth of ψ from 0 to $\frac{\pi}{2}$ the radii of circular orbits grow continuously from R_3 to R_4. Here there is a class of circular orbits. We call them the II-class of circular orbits.

Taking into account that w is given by formulas on intervals [2, p. 80-82]

$$\alpha_2 \le w \le \alpha_1,\ w = \frac{\alpha_2\alpha_{31} - \alpha_3\alpha_{21}\sin^2\psi}{\alpha_{31} - \alpha_{21}\sin^2\psi},\ 0 \le \psi \le \frac{\pi}{2}, \tag{13}$$

$$\alpha_4 \le w \le \alpha_3,\ w = \frac{\alpha_4\alpha_{31} + \alpha_1\alpha_{43}\sin^2\psi}{\alpha_{31} + \alpha_{43}\sin^2\psi},\ 0 \le \psi \le \frac{\pi}{2}, \tag{14}$$

let us check the boundaries of the circular orbits of the I and II classes.

We consider the boundaries of circular orbits of the I class:
at $\psi = 0$ from (13) we have

$$R_1 = w_1 = \frac{\alpha_2\alpha_{31}}{\alpha_{31}} = \alpha_2, \tag{15}$$

at $\psi = \frac{\pi}{2}$ we have

$$R_2 = w_2 = \frac{\alpha_2(\alpha_1 - \alpha_3) - \alpha_3(\alpha_1 - \alpha_2)}{(\alpha_1 - \alpha_3) - (\alpha_1 - \alpha_2)} = \frac{\alpha_1(-\alpha_3 + \alpha_2)}{(-\alpha_3 + \alpha_2)} = \alpha_1. \tag{16}$$

The lower boundary α_2, the upper α_1, as $\alpha_1 > \alpha_2$.

We consider the boundaries of circular orbits of the II class:
from (14) with $\psi = 0$ we get

$$R_3 = w_3 = \frac{\alpha_4\alpha_{31}}{\alpha_{31}} = \alpha_4, \tag{17}$$

at $\psi = \frac{\pi}{2}$ we have

$$R_4 = w_4 = \frac{\alpha_4(\alpha_1 - \alpha_3) + \alpha_1(\alpha_3 - \alpha_4)}{\alpha_1 - \alpha_3 + \alpha_3 - \alpha_4} = \frac{\alpha_3(\alpha_1 - \alpha_4)}{\alpha_1 - \alpha_4} = \alpha_3. \tag{18}$$

The lower boundary α_4, the upper α_3, as $|\alpha_4| < \alpha_3$.

According to (16) the I class of circular orbits originates from α_2 and ends with the value α_1, merging into one orbit of the radius $R_2 = \alpha_1$.

According to (17) and (18) The II class of circular orbits starts from the orbit of the radius $R_3 = \alpha_4$ merging into one orbit of the radius $R_4 = \alpha_3$.

Thus, we consider the availability of 2 classes of circular orbits that are not related to each other as authentic.

As in the case of the I class, so in the case of the II class, the radii of circular orbits continuously grow and merge into one orbit, the radius of which is the largest in each of the classes.

From circular orbits in Hill variables $w = \frac{C^2}{\mu}\cdot\frac{1}{\rho}$ we proceed to actual circular orbits $\rho = \frac{C^2}{\mu}\cdot\frac{1}{w}$, then the boundaries of the orbits of the I class have the form:

$$\rho_2 = \frac{C^2}{\mu}\cdot\frac{1}{\alpha_1},\quad \rho_1 = \frac{C^2}{\mu}\cdot\frac{1}{\alpha_2},\quad \alpha_1 > \alpha_2,\ \rho_1 > \rho_2,$$

with ρ_1 – the upper boundary, ρ_2 – the lower boundary of this class of circular orbits (figure 2).

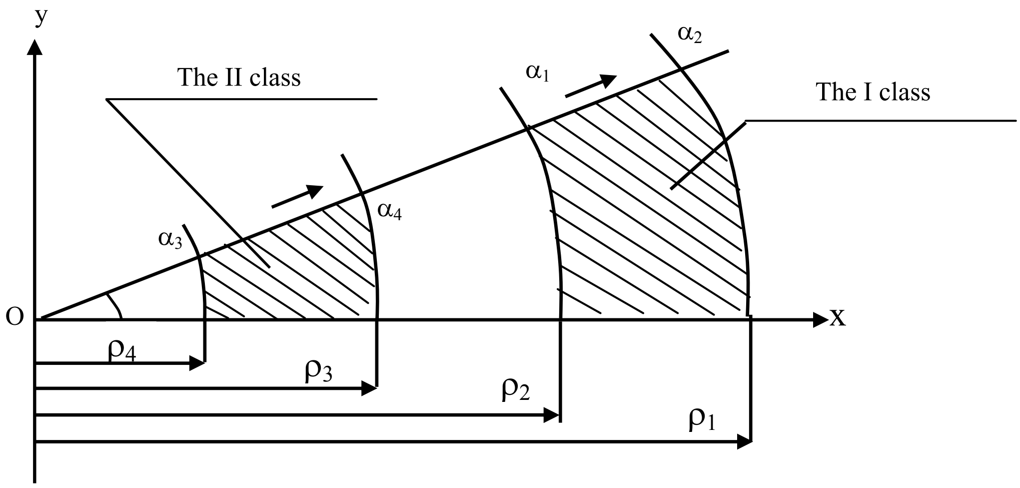

Figure 2 – The boundaries of actual circular orbits

The I class of actual circular orbits begins with ρ_2 and merge into one orbit of the radius ρ_1.

For actual circular orbits of the II class we have:

$$\rho_3 = \frac{C^2}{\mu} \cdot \frac{1}{\alpha_4}, \quad \rho_4 = \frac{C^2}{\mu} \cdot \frac{1}{\alpha_3}, \quad \alpha_3 > |\alpha_4|, \; \rho_3 > \rho_4,$$

ρ_3 – the upper boundary, a ρ_4 – the lower boundary of this class.

Thus, The II class of actual circular orbits begins with ρ_4 , merge into one orbit of the radius ρ_3.

As ψ rises up to $\frac{\pi}{2}$ the radii of the orbits of the I class grow continuously from ρ_2 to ρ_1, similarly, the radii of the orbits of the II class increase from ρ_4 to ρ_3.

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ХИЛЛ АЙНЫМАЛЫЛАРЫНДА СЫНАҚ ДЕНЕСІНІҢ ЕКІ ШЕҢБЕРЛІК ОРБИТАЛАР ҮЙІРІ БАР БОЛУЫ

Аннотация. Б. М. Щиголев жазықтықтағы Хилдың екінші есебін зерттеді [1, б. 119]. Бұл есепте Хилл күш функциясы мына түрде берді

$$U = \frac{\mu}{r} + \frac{1}{2}\nu r^2, \quad r^2 = x^2 + y^2, \quad \nu > 0, \quad \mu = f(m_0 + m),$$

мұнда m_0 – орталық дененің массасыҢ m – сынақ денесінің массасыҢ f – тартылыс тұрақтысы.

Күш функциясының құрамы перицентр қозғалысын (және кеңістікте түйін қозғалысын) есепке алатын етіп алынған.

Б. М. Щиголев [1, б. 98] өзінің жеке әдісін қолданып шеңберлік орбиталар туралы өте құнды мәліметтер алды:

1. $\alpha < 0{,}10546875$ болғанда екі шеңберлі орбиталар бар.

2. Олар жалғыз орбита $\alpha = 0{,}10546875$ болғанда айналады.

3. $\alpha > 0{,}10546875$ болғанда орбита жойылады.

Мақалада бұл мәліметтер орындалатындығы және шеңберлік орбиталардың бір-бірімен байланыссыз екі үйірі бар екені айтылды. Ол үйірлердің шектері табылды.

Түйін сөздер: сынақ денесі, шеңберлік орбита, Хилл айнымалылары, орбита үйірі, Хилл өрісі, Жердің жасанды серігі.

М. Д. Шинибаев[1], А. А. Беков[1], Б. Н. Рахимжанов[1], С. Б. Моминов[1], А. Ж. Садыбек[2], Б. Т. Алимкулова[3], К. Абдрахманов[3]

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О СУЩЕСТВОВАНИИ ДВУХ КЛАССОВ КРУГОВЫХ ОРБИТ ПРОБНОГО ТЕЛА В ПЕРЕМЕННЫХ ХИЛЛА

Аннотация. В работе [1, с.119] Б. М. Щиголев исследовал плоскую вторую задачу Хилла. Для нее Хилл предложил схему силовой функции:

$$U = \frac{\mu}{r} + \frac{1}{2}\nu r^2, \quad r^2 = x^2 + y^2, \quad \nu > 0, \quad \mu = f(m_0 + m),$$

где m – масса центрального тела; m_0 – масса пробного тела; f – постоянная тяготения.

Структура силовой функции мотивируется тем, что в плоской задаче учитывается движение перицентра (и узла в пространственной задаче).

Б. М. Щиголев, минуя общеизвестные представления о круговых орбитах во второй задаче Хилла, используя свой оригинальный способ, нашел [1, с. 98] следующие закономерности существования и эволюции круговых орбит пробного тела:

1. При $\alpha < 0{,}10546875$ существуют две круговые орбиты.

2. Эти орбиты сливаются в одну при $\alpha = 0{,}10546875$.

3. Они исчезают при $\alpha > 0{,}10546875$.

В статье показана справедливость этих выводов и в случае возмущенной плоской задачи Хилла. Установлено существование двух классов круговых орбит в переменных Хилла. Найдены границы этих классов, как в переменных Хилла, так и в действительных переменных. Найденные закономерности справедливы как в плоской задаче, так и в случае малого наклона орбиты к основной плоскости.

Ключевые слова: пробное тело, круговые орбиты, переменные Хилла, класс орбит, поле тяготения Хилла, спутник Земли.

CONTENT

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