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R u s s i a n A c a d e m i e o f S c i e n c e

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**Researches**  
**of Asteroids and Comets;**  
**Flights with Low Thrust.**

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## **Researches of Asteroids and Comets; Flights with Low Thrust.**

Two reports, presented on the 17 Space Flight Dynamics Conference, are joined by their attention to researches of small celestial bodies – asteroids and comets, and by supposed use of spacecrafts with low thrust for those purposes. For more than 20 years we do research the problem of flights towards asteroids of the Main Belt and comets of Jupiter group with the help of low thrust (see References). As it is supposed that above mentioned small bodies may conserve the relic matter and may carry important information about Solar System origin. Recently a conception (based on our knowledge of small bodies) of Space Patrol system for discovering of hazard asteroids approaching the Earth was formulated. It may extend known programs of optical observation of hazard objects from the Earth.

### **Исследование астероидов и комет и полеты с малой тягой.**

Два доклада на конференции «Space Flight Dynamics» посвящены изучению малых тел, астероидов и комет и полетам с малой тягой. Полеты с малой тягой к малым телам исследовались нами более 20 лет. Реликтовое вещество их может дать ответ на загадки происхождения солнечной системы. Вопрос об астероидной безопасности Земли приводит к концепции о системе космического патрулирования, также с возможностью использования малой тяги.

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### **SPACE PATROL SYSTEM.**

***ABSTRACT.** Conception of a space patrol system destined to discover celestial bodies that may be dangerous for Earth is considered. The patrol system consisting of several spacecraft located on the Earth orbit around the Sun with space telescopes onboard will allow to discover asteroids approaching the Earth orbit. The overwhelming majority of such bodies with diameters  $\geq 100$  m may be defined during 5-6 years and the catalogue of their orbits may be done. Some known scientific programs of observing such celestial bodies from the Earth supposes to make a catalogue of  $\approx 95\%$  of bodies with diameter  $\geq 1$  km till 2010 year. Hence the system of space observation may be considered as the following step in the program of observation of dangerous objects.*

*Our conception is based on the theory of origin of dangerous asteroids and evolution of their orbits. Description of “optical barrier” created by patrol system is given and some principal parameters of the system are analyzed. It’s proved that the system of space telescopes may be put on the necessary orbits with the help of spacecraft with electro-rocket propulsion. The project of such spacecraft is now worked out for the expedition “Fobos-Ground”.*

*The work is supported by RFBR, grants 01-01-00015, 00-15-96036.*

**KEYWORDS:** asteroid hazard, low thrust, optical observation.

## **INTRODUCTION.**

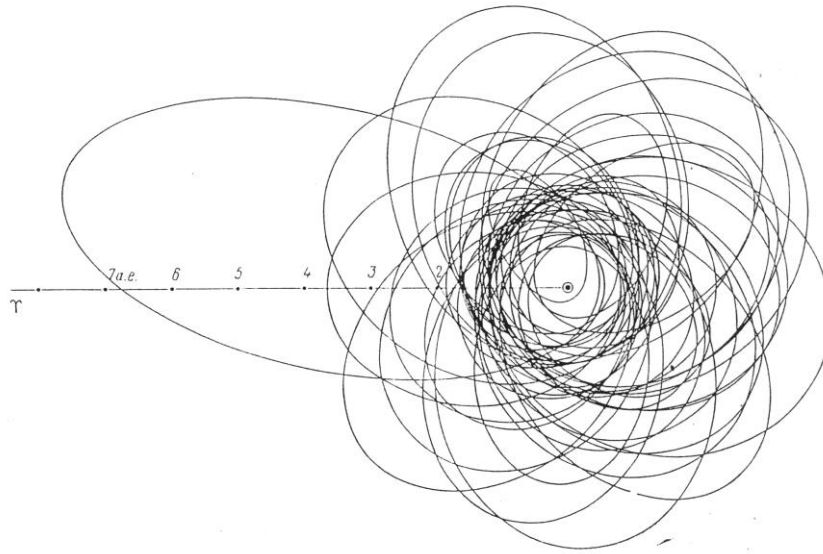
The problem of Asteroid Hazard attracts the attention of scientists and society in the whole world. Researches of catastrophe marks on the Earth surface, which has the cosmic origin, observation of asteroids approaching the Earth and of so called astro-catastrophes of the XX century (Tunguska meteorite etc) proves the reality of asteroid hazard for civilization existence and the necessity of working out the means of counteraction. Books [1-3], scientific conferences, journals (specialized journal “Bolshaya Medvedica” in Novosibirsk) pay attention to this problem. Two main sub-problems must be pointed out in this problem: definition of hazard objects and counteraction to possible collision. There are several programs of optical observation of celestial bodies approaching the Earth (American, English-Australian, and others). They expect to discover the most part of bodies with diameter  $\geq 1$  km in the nearest years. Other projects investigate the possibility of comprehensive space technologies to change the orbits of dangerous objects or to destruct them into small fragments that would be burnt in atmosphere. Russian scientists and engineers and leading Russian cosmic firms also take part in such researches. However the mentioned programs of space observation from the Earth allow to find mainly relatively large objects (one km in diameter or more), while much more less celestial bodies may also be dangerous (Tunguska meteorite is estimated to be of 50-70 m in diameter). Space Patrol System, described in this report, propose to make observations from onboard space telescopes, which will build so called “optical barrier” in the vicinity of Earth orbit and will allow to discover during 5-6 years the majority of dangerous bodies with diameter  $\geq 100$  m.

### **Population of Near-Earth Asteroids.**

Now there is no doubt in relevance and seriousness of asteroid hazard problem. Up-to-date observational technology has extended our ability of observing and discovering the small bodies (asteroids and comets) in the vicinity of circumsolar Earth orbit and helped us to get a new view of this problem and estimate it's real scale. At the moment there are known several hundreds of small bodies with diameters from some meters to some kilometers which orbits intersect the Earth orbit. Their general characteristic is that the aphelion (the farthest from the Solar point on the orbit) as a rule does not exceed the Jupiter orbit. That is to say these celestial bodies belong to Aton or Apollo groups (fig.1,2). Statistics show that the quantity of such small bodies may exceed a hundred thousand. The quantity of bodies with diameter  $\geq 1$  km exceeds a thousand. Some important conclusions may be based on these data. Firstly the probability of Earth percussion with celestial bodies of dangerous size is really large. In favor of this conclusion says the fact that there was at least two catastrophic percussions with cosmic objects in the XX century (fortunately happened in desolate regions): Tunguska catastrophe on June 30, 1908, and catastrophe in desolate region of Amazon on August 13, 1930.

Secondly our attention must be concentrated on bodies with relatively small eccentricity of the orbits – like asteroids of Aton, Amour, Apollo groups or short-periodic comets of Jupiter group. As for the bodies with large orbit eccentricity, intersecting the Earth orbit – their quantity is small and now may be not

considered. Thirdly we have to settle the period of time in which the asteroid hazard may be considered as practically actual for mankind. Perhaps at the first a century may be taken for such period.

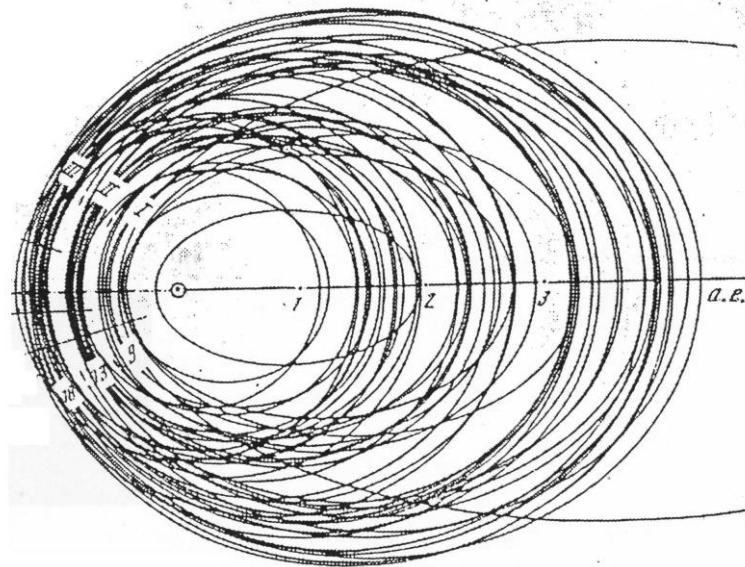


**Fig. 1. Example of Near-Earth Asteroid's orbits.**

Below we will consider the sub-problem of discovering and cataloguing potentially hazard asteroids as preclusive to another sub-problems in complex problem. Though another sub-problems, say of counteracting to possible percussion, must be theoretically investigated simultaneously, practically they can be effectively solved only after the general situation with hazard asteroids (how many and what types of bodies may threaten the Earth in a given period of time) will be defined: apparently different means must be worked out for counteracting to the huge bodies (with  $\geq 1$  km in diameter) and the small ones ( $\approx 100$  m).

In the problem of discovering and cataloguing potentially hazard asteroids let's set the next task: is it possible to make for a few years a catalogue of bodies, that may come into collision with Earth in the succeeding hundred years, and what technical means will be adequate today for solving this problem.

It was mentioned above that the catalogue of known asteroids crossing the Earth orbit includes mainly the small bodies with orbit aphelion inside the Jupiter orbit. Their perihelion (the nearest to the Solar point of an orbit) as a rule lies between Venus and Earth orbits. Hence large semiaxis of their orbits does not exceed 3 astronomical units (a.u.). From a third Kepler law the high border of orbit time for these asteroids can be calculated. It does not exceed 6 years. Therefore asteroids of this group will cross the vicinity of the Earth at least once during any 5.5-6 years. It's a very important circumstance. If one could establish an effective patrol observing of the Earth vicinity – then all objects accessible to space telescope resolution should be recorded during 5.5-6 years. One possible scheme of a patrol system will be described below. But previously one important aspect of the problem must be noted.



**Fig.2. Asteroid's orbits with superposed apside lines. We can see three intervals in orbit's – result of resonance with Mercury, Venus and the Earth.**

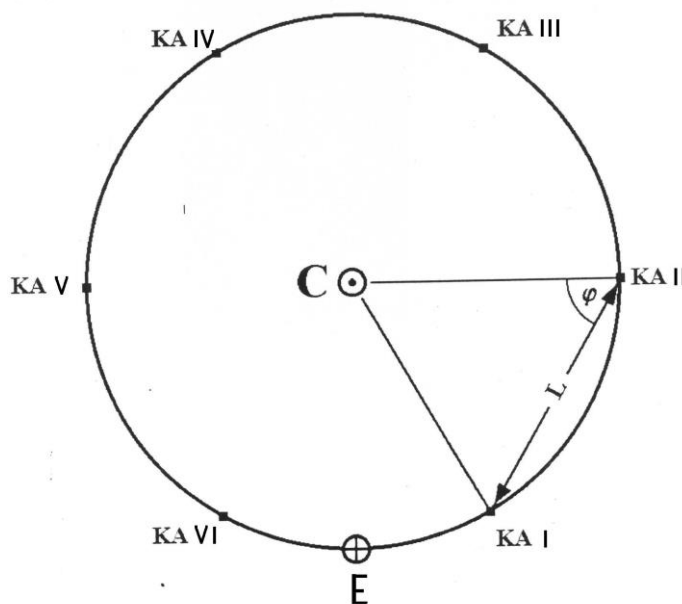
Asteroids of Apollo group as well as of Aton and Amour groups are not permanent inhabitants of the zone of Earth planet group and asteroid Main Belt (i.e. zone overspread from the Mercury orbit to the Jupiter one). Due to influence of big planets asteroid orbits are disturbed and sooner or later they approach Jupiter, enter it's gravisphere, obtain the additional energy and thereafter abandon the zone of Earth planet group by high elliptical orbit or even the Solar system itself by hyperbolic orbit. So a peculiar process of diffusion occurs in these groups. But a number of scientists sure that population of Aton, Amour and Apollo groups is rather steady and its' quantity didn't change greatly in the Solar system history. Hence some source supplying the groups of asteroids with new members must exist. Now the problem of the source is not completely studied. A model of Solar System formation worked out in the seventies in Keldysh Institute [1,2] gives much for understanding of origin of small bodies population, approaching the Earth. On the base of this model a supposition of trans-Neptune belt existence was done in 1980 [3]. Up to date a lot of asteroids of trans-Neptune belt is already discovered. It's supposed that Edgeworth-Kuiper Belt may be the source. An important contribution to the theory of celestial bodies migration from trans-Neptune areas into Earth region was done by Kazimirchak-Polonskya. Her investigations have revealed the mechanism of small bodies migration. These problems have also been studied in the works of S.I.Ipatov [4]. Anyhow it's more important that such source exists and that processes of diffusion and of resupply hold the balance in the size of groups. The average time of asteroid stay in the Earth planet group zone is estimated to be 10-100 million years. Though it's not large period of time in comparison with the Solar system age, it's much more longer than the specific time in our problem (100 years). That's why one can ignore the possibility of unexpected appearance of new (moreover of dangerous) asteroid in considered groups. The chance of such event is rather small. It's even less than the chance of collision with bodies with high-elliptical orbit. Hence in the

scope of asteroid hazard problem the quantity of observing bodies and their composition may be considered as invariable in the practically important period of time.

### Space Patrol System and conception of “optical barrier” in the Earth orbit.

Now let’s consider the technical means suitable for the problem of cataloguing the bodies crossing the Earth orbit vicinity. Let’s imagine the pseudo cylindrical surface with an axis perpendicular to the Earth orbit plane and containing the Earth orbit. If one could control this surface with the help of optical observation – then all objects with apt sizes that enter it’s vicinity would be checked. Observation could be arranged by the system of spacecrafts located on the circum Solar Earth orbit provided with onboard telescopes with high optical resolution. One onboard telescope rotating around the Solar-directional axis would be enough for permanent rescan of a circular strip on the coelosphere. The width of a strip depends on the telescope vision angle. Telescope direction and angular velocity of its rotation must be arranged to solve the principal task.

Patrol system may consist of  $N$  spacecrafts (in fig.3  $N=6$ ), evenly distributed on the circular orbit. The distance  $L$  between each pair of spacecrafts must be kept invariable. The larger number  $N$  of spacecrafts – the smaller distance  $L$  between them. For  $N=6$   $L=1$  a.u. and angle  $\varphi=60^\circ$ . The plane of scanning may coincide with the plane that contains neighboring spacecrafts. In this case areas scanned by telescopes will partly intersect. This will enhance the reliability of the Patrol system because the



**Fig. 3. Location of Space Patrol System in the Earths orbit.**

nearest areas of telescope are not fully controlled by it along of its rotation. Some asteroids with big angular velocity (which inversely proportional to the distance between asteroid and telescope) may cross the area unchecked. But they must be checked from the next spacecraft because their angular velocity will be not large relative to the next telescope. Thus the principal “working distance” of each

telescope will be greater than some  $L_{\text{MIN}}$  ( $L_{\text{MIN}} \leq L/2$ ), though many objects can be checked on smaller distance.

In order to estimate roughly the orbital parameters of checked asteroid it is desirable to locate it at least for four times while it crosses the visible area. Preliminary processing of optical data – distinguishing of moving object against fixed stars, estimation of its angular velocity and determination of orbital parameters – is planned to make on a board computer. As one can see for represented in fig.3 configuration of patrol system all 6 spacecrafts are within the field of radio vision from the Earth (none of them is covered by Sun). Thanks to radio communication operatively all suspicious cases could be additionally verified on the Earth to raise the trustworthiness of results.

Technical characteristics of up-to-date telescopes (1 m in diameter; 2 sq degrees, or almost 1.5 angular degrees of vision area) allow checking from the Earth celestial bodies of 22<sup>ND</sup> star magnitude. Approximate estimation, dependant on the asteroid surface albedo, shows that such telescopes will be able to detect asteroids with diameter at least of 250 m at distance of 1a.u., or 125 m at distance of 0.5a.u.

Consideration of asteroid hazard problem inevitably raises the question about basic space technique that could be used for realization of patrol system. It seems that the launcher of “Souz”-type (“Molnia”) could be used for boosting of spacecraft to the interplanetary orbit. The consequent transfer to circum-Solar orbit could be done with the help of spacecraft with electro-rocket propulsion that is now worked out for the “Fobos-Ground” project [5]. That same spacecraft can also provide the functioning of all the necessary systems of patrol: electro-rocket engines – support the orientation of spacecraft and correct its orbit, solar arrays – provide with electric energy the work of telescope, onboard computer, radio communication and other devices.

### **Arrangement of Patrol System on the circum Solar Earth orbit.**

Calculations were done for the system, represented in fig.3. Two variants were considered. One – with the use of conventional high thrust (i.e. chemical engines), another – with the use of perspective low thrust (i.e. electro-rocket propulsion). For the “Fobos-Ground” project an universal Space System is now worked out. It supposes to use a launcher “Molnia” and a spacecraft with electro-rocket engines and solar arrays. The launcher is able to place 2 tons into hyperbolic (geocentric) flight trajectory. Solar arrays provide 7 kW of nominal electric power (on the distance of 1 a.u. from the Sun), or 3.5 kW of jet power. The exhaust velocity of jet is 24 km/s.

In table 1 the results of placing the spacecraft into different points of circular orbit are represented. Here  $T$  and  $\Phi$  are duration and angular distance of a maneuver;  $N$  is the number of position in fig.3, where the spacecraft had to be placed (the data are given for three most energy-expensive points);  $M_K$  is the final mass of spacecraft. Index “ID” means the “ideal model” of low thrust, when the exhaust velocity gets the optimal value and is variable on a trajectory. Index “ST” means the “stepped model”, when the exhaust velocity is invariable on the active parts of

the trajectory.  $M_{WS}$  is a mass of working substance;  $M_{PL}$  is a payload mass:

$$M_{PL} = M_F^{ST} - 0.2 M_{WS} - M_{ERA}.$$

Here  $M_{ERA} = 320$  kg is the mass of electro-rocket engines and Solar arrays;  $0.2M_{WS}$  is the mass of tanks.

**Table 1.**

N	$\Phi$ [orbits]	T [year]	$M_F^{ID}$ [ton]	$V_J$ [km/s]	$M_F^{ST}$ [ton]	$M_{WS}$ [ton]	$M_{PL}$ [ton]
3	3.42	3	1.895	24	1.761	0.239	1.393
4	2.58	3	1.846	24	1.730	0.270	1.356
5	1.75	2	1.811	24	1.697	0.303	1.316

For comparison the results of placing the spacecrafts into the same positions on the circular orbit with the help of high thrust are given in table 2. Here  $\Delta V$  is the full impulse of maneuver (i.e. characteristic velocity of an optimal trajectory);  $M_F^{ST}$  is the final mass (for stepped model of low thrust). These results show that the use of low thrust is more advantageous. Delivered payload mass is almost 200 kg greater against the final mass  $M_F$  of spacecraft for variant with high thrust. (In table 2 in the last column is given the final mass instead of payload one. The payload mass will be at least 100 kg smaller.) What is also important – the electro-rocket engines, Solar arrays and other devices of spacecraft may be used as part of the Patrol System.

**Table 2.**

N	T [year]	$V_J$ [km/s]	$\Delta V$ [km/s]	$M_F^{HT}$ [ton]
2	3	3.2	1.693	1.178
3	3	3.2	1.720	1.168
4	2.5	3.2	1.076	1.429

### Resume.

A scheme of discovering asteroids approaching the Earth, with the help of Space Patrol System, located on the circumsolar Earth orbit is suggested. It will allow to check hazard asteroids with diameter of one and more hundreds meters. Therefore it may be considered as an additional program of investigation of hazard asteroids that will prolong the existing programs of optical observation of such bodies from the Earth. A spacecraft with low thrust the same as in “Fobos-Ground” project may be used for forming of a Patrol System – for placing spacecrafts with onboard telescopes on the circular orbit.



## **MAIN BELT ASTEROID MISSIONS WITH LOW THRUST AND GRAVITY ASSIST OF MARS.**

**ABSTRACT.** *The ability of flights to the Main Belt asteroids (such as Fortuna, Lutecia etc) of spacecraft with low thrust on solar arrays is considered. The goal of such flights – delivering of relic ground sample to the Earth. Calculations shows that the spacecraft which is now worked out for the “Fobos–Ground” project, cannot deliver the necessary payload to asteroid (necessary for sample return). But missions becomes possible if : 1. the assist of Mars will be used, or 2. the power of solar arrays will be increased .In the first case about twenty variants of missions were found for asteroids of all the main types (C,S,E,I,M,O,U). In the second case the twice increasing of the solar arrays power will allow to realize the straight flights to many asteroids of the main belt. So the spacecraft destined for “Fobos-Ground” project may be used for Main Belt missions with relic ground sample return to the Earth.*

*The work is supported by RFBR, grants 01-01-00015 and 03-01-00864.*

**KEYWORDS:** asteroid, low thrust, gravity maneuver, ground sample return.

### **INTRODUCTION.**

This paper considers the possibility of use of spacecraft now worked out for the “Fobos-Ground” project in the mission to the Main Belt Asteroid. The goal of such mission is delivering of relic matter from asteroid to the Earth. The problem of space flights to the Main Belt asteroids with delivering of soil sample from them to the Earth is of great scientific importance. It may give answers to many questions about processes of Solar system origin and for the sciences about the Earth. These expectations derive from the cosmogonical conception, founded on the computer’s model of Solar system formation [1]. In accordance with this model differentiation of the matter in an initial disk with increasing distance from Sun led to differentiation of the planet matter. Detection of such differentiation with the help of isotopic and mineralogical analysis is one of the goals of space missions.

10 years ago the United group of Soviet and German scientists and engineers had worked out a project of new Universal Space System destined to solve numerous problems of Solar system investigation, that couldn’t be solve with the help of conventional space technology [6,7]. It supposed to use the launcher “Proton” and a spacecraft with electro-rocket propulsion and an onboard nuclear power plant. The top priority mission offered in a project was a mission to asteroid “Fortuna” with ground sample return to the Earth. The next scheme of a flight was suggested. The spacecraft had to be boosted into interplanetary orbit with the help of high thrust (block “D”); the consequent flight to asteroid with equalization of asteroid and spacecraft velocities – with the help of low thrust (electro-rocket engines); at rendezvous with asteroid a special lander module had to take a soil sample, ascend

from the asteroid and then return to the Earth with the help of high thrust engines. Characteristics of spacecraft and of optimal trajectory are the next. The initial mass of spacecraft (on the interplanetary part of the mission) is 6 tons, half of it is the mass of nuclear power plant; electric power is 30 kW; geocentric hyperbolic excess velocity is 3 km/s; duration of flight towards asteroid – 2 years, the backward flight to the Earth – half a year, the full time of the mission – 4 years. The positive property of the nuclear power plant is rather large electric power, which practically does not depend on time or distance. Negative one – its large mass, what make necessary the use of rather expensive launcher “Proton”. Calculations of optimal flights with low thrust on solar arrays to several asteroids of the Main Belt have been done in [8].

Technical characteristics of the system worked out for “Fobos-Ground” mission are relatively modest [5]. More light and cheap launcher of “Souz” type and light solar arrays are supposed to be used instead of “Proton” and nuclear plant. Initial mass of spacecraft is 2 tons (3 times smaller); nominal electric power – at a distance 1 astronomical unit – is 7.5 kW (4 times smaller); hyperbolic excess velocity is 1.75 km/s; the mass of transport block, electro-rocket engines and solar arrays is  $M_{ERA} = 0.3$  ton. The payload mass delivered to Fobos is about 0.9 ton:

$$M_{PL} = M_F - M_T - M_{ERA}.$$

– it’s the final mass  $M_F$  of spacecraft without masses of tanks  $M_T = 0.2 \cdot M_{WS}$  ( $M_{WS}$  is the mass of working substance) and above mentioned  $M_{ERA}$ . The positive property of solar arrays – their small mass; negative – the small nominal electric power and its decreasing with moving away from the Sun (near Fortuna the power becomes five times smaller). No wonder that Fortuna mission, as well as missions to another asteroids of the Main Belt, becomes impossible. Even with increasing of flight time towards asteroid from 2 to 3 years the payload mass near Fortuna does not exceed 0.7 ton (our analysis is based on the supposition that about 0.9 ton of payload mass – the same as delivered to Fobos – must be near asteroid). In table 1 index “ID” means an ideal model of low thrust (exhaust velocity  $V_J$  changes to get an optimal value); index “ST” means stepped model of low thrust ( $V_J = 16.5$  km/s on active parts of trajectory);  $\varphi$  – angular distance of flight;  $M_K$  – the final mass of spacecraft;  $M_{PL}$  – the payload mass near the asteroid.

**Table 1.**

$N_E^0$	T	$\varphi$	$M_F^{ID}   M_F^{ST}$	$V_J$	$M_{PL}^{ID}   M_{PL}^{ST}$
[kW]	[years]	[degrees]	[ ton ]	[ km/s ]	[ ton ]
7.5	3	540	1.202	id	0.753
			1.151	16.5	0.692

### **Missions to Main Belt Asteroids with gravity assist of Mars.**

There are two principal ways of increasing the payload mass. The first one – is to use the gravity assist of Mars. The second one – to increase the nominal power of

Solar arrays. The use of perturbative maneuver in Mars's gravity sphere may considerably increase the payload mass – sometimes half as much again as the straight flight from the Earth to asteroid. Some parameters of the combined mission to Fortuna are given in table 2. The name of asteroid, its geochemical type and its index by catalogue are given in column 1. Characteristics of spacecraft and of optimal trajectory (towards asteroid), the same as in table 1, are given in column 2. The backward impulse  $\Delta V$  of high thrust, given near the asteroid for return to the Earth, the date  $t_s$  of start from the Earth and the full duration  $T_M$  of the mission are given in the third column. The full time  $T_M$  includes the time of accompanying of asteroid by spacecraft while waiting for the opportunity for backward start. In addition to stepped program of low thrust with exhaust velocity  $V_J = 16.5$  km/s the program with two levels of  $V_J$ : 16.5 and 25 km/s is also considered. Ideal model of low thrust gives the best possible value of payload mass. The stepped model – with one level of exhaust velocity  $V_J$  – may sometimes differ considerably from the ideal model. The stepped model with two levels of  $V_J$  as a rule rather similar to the ideal model by delivered mass. In the present case the last variant gives much greater payload mass than the first one. But it supposes the use of two types of electro-rocket jet engines. Meanwhile the “Fobos-Graund” project provides engines of only one type.

**Table 2.**

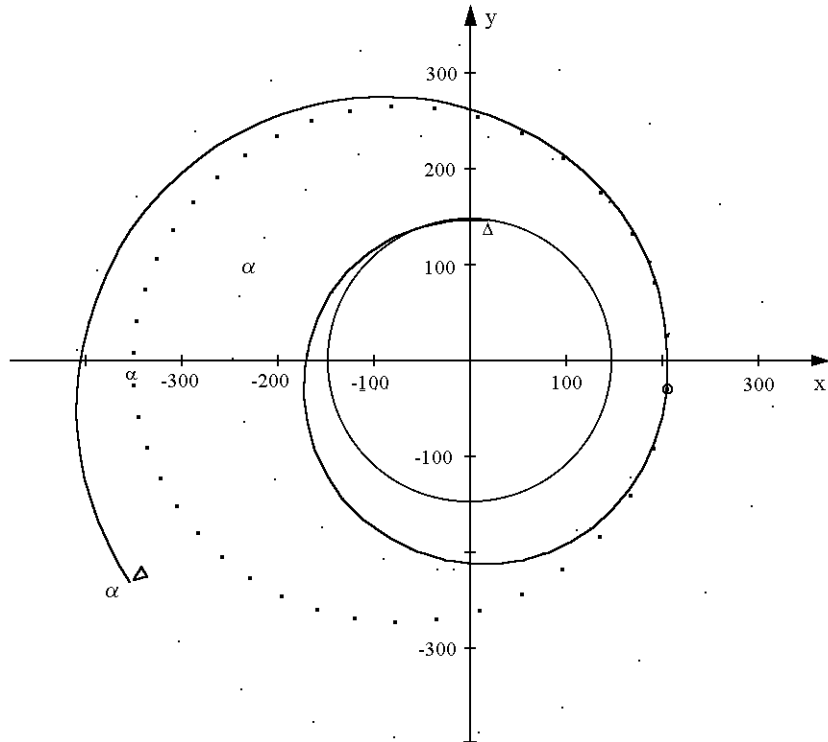
N тип	$N_{\odot}^0$	T	$\varphi$	$M_F^{ID}/M_F^{ST}$	$V_J$	$M_{PL}^{ID}/M_{PL}^{ST}$	$T_E$	$T_M$	$\Delta V$
	[kW]	[year]	[degree]	[ton]	[km/s]	[ton]			
19 C	7.5	3.3	514	1.541	id	1.160	02.2093	6.48	4.2
				1.363	16.5	0.946			
				1.472	16.5+25	1.077			

An example of optimal flight towards Mars and consequent flight to Fortuna is given in fig.1. Here the Earth orbit and spacecraft's trajectory are given in firm line; the orbits of Mars and asteroid – in dotted lines; the osculating orbit of spacecraft after exit from Mars's gravisphere – in bold dotted line. Sympol  $\alpha$  marks the aphelion of orbits,  $\nabla$  – the points of start from the Earth and finish near Fortuna,  $\odot$  – the flyby of Mars.

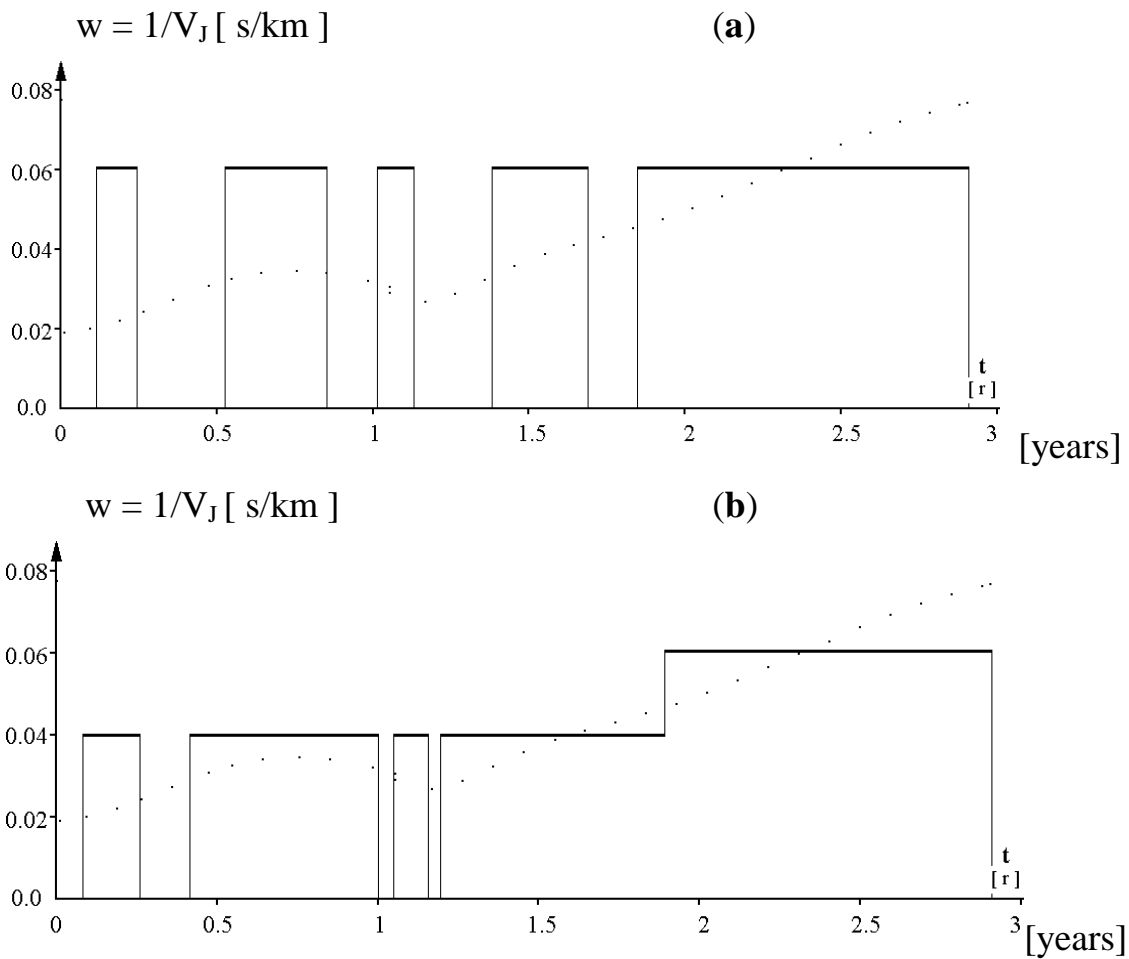
Two examples of stepped program of low thrust, or rather of inverse value of exhaust velocity  $w = 1/V_J$  are given in fig.2, (a) and (b) in firm lines, the ideal one – in dotted lines.

It's immediately obvious that the program with two levels of exhaust velocity much better approximates the ideal one, than the program with one level, and therefore gives better payload mass.

Unfortunately the assist of Mars may be helpful very seldom, because the lucky disposition of three planets – Earth, Mars and asteroid – is necessary. As the ratio



**Fig.1. Trajectory of optimal flight to Fortyna with gravity assist of Mars.**



**Fig.2. Examples of optimal stepped and ideal programs of inverse value of exhaust velocity.**

of Fortuna and Mars periods is equal to 2.03, resemblant disposition happens only once in 125 years. That is why the next occasion for the Earth-Mars-Fortuna mission will be only in 2093 year. Such rare opportunity of missions with assist of Mars has raised the question about other objectives for flight. As there are hundreds of asteroids with diameter  $\geq 50-100$  km and thousands of all known up to date asteroids of the Main Belt, many interesting variants of missions can be suggested. As the great opposition of Mars and Earth happens every 15-17 years, the start dates of these missions form groups with approximately the same period.

16 variants of missions towards asteroids mainly from the first two hundreds by catalogue (and therefore with large sizes) with start dates in the 21<sup>ST</sup> century are found. It's important that this list includes the missions to asteroids of all the main geochemical types: C, E, I, M, O, S.

**Table 3.**

N type name	$t_E$ $\Delta T_1$ [days] $\varphi_1$ $t_M$ $\Delta T_2$ $\varphi_2$ $t_A$ $\Delta T_\Sigma$ [y] $\varphi_\Sigma$ [orb]	$V_{ENR}$ $\gamma$ $\omega$ $R_M$ $R_A$ [km/s] [mln.km]	$M_F$ $M_{PL}$ [ton] [ton]
64 E Angelina	30.10.2011 273 196° 29.07.2012 1027 348° 22.05.2015 3.56 1.51	3.748 56° 2°.2 231 395	1.499 1.109
32 S Pomona	28.01.2016 204 165° 20.08.2016 909 287° 15.02.2019 3.05 1.26	5.167 37° 9°.6 212 356	1.330 0.906
215 Oenone	24.02.2016 335 236° 24.01.2017 858 259° 31.05.2019 3.27 1.37	2.949 72° -6°.3 214 404	1.400 0.990
30 S Urania	18.12.2028 393 262° 15.01.2030 671 234° 17.11.2031 2.91 1.38	3.353 63° -11°.1 207 398	1.504 1.115
177 C Irma	15.12.2028 384 257° 03.01.2030 847 233° 28.04.2032 3.37 1.36	3.136 67° -5°.8 207 511	1.471 1.075
178 S Belisana	26.11.2030 284 229° 06.09.2031 900 285° 22.02.2034 3.24 1.43	3.607 58° 0°.7 212 356	1.548 1.168

Some of these variants are represented in tables 3 and 4. In table 3 are given:  $t_E, t_M, t_A$  – the dates of start from the Earth, flyby of Mars and rendezvous with asteroid;  $\Delta T_1, \Delta T_2, \Delta T_\Sigma$  – duration of the flight from the Earth to Mars in days,

from Mars to asteroid (in days) and from Earth to asteroid in years;  $\varphi_1, \varphi_2, \varphi_\Sigma$  – angular distance of flight between Earth and Mars, Mars and asteroid (in degrees) and Earth and asteroid (in orbits);  $V_{ENR}, \gamma, \omega$  – the module of spacecraft’s entry velocity (into the sphere of Mars) and two angles of it’s orientation;  $R_M, R_A$  – heliocentric distance of Mars and asteroid at rendezvous moments (in million km).

In table 4 are given:  $t_E$  – the date of start from the Earth,  $\Delta T_P$  – the time of waiting near the asteroid for backward start opportunity to Earth;  $\Delta T_B$  duration of backward flight;  $T_M$  – full duration of the mission;  $\Delta V$  – the impulse of high thrust near asteroid for return to the Earth.

**Table 4.**

$t_E$ type N	$M_{PL}$ [ton]	$\Delta T_P$ [y]	$\Delta T_B$ [y]	$T_M$ [y]	$\Delta V$ [km/s]	$\Delta T_P$ [y]	$\Delta T_B$ [y]	$T_M$ [y]	$\Delta V$ [km/s]
2011 E 64	1.109	0.13	1.27	4.95	5.0	1.27	1.39	6.22	4.0
2016 S 32	0.906	0.61	1.17	4.83	5.4	1.90	1.30	6.25	4.2
2016 215	0.990	0.57	1.11	4.94	5.4	1.71	1.24	6.21	5.0
2028 S 30	1.115	–**	1.11	4.04	5.1	–0.17*	1.20	3.95	4.3
2028 C 177	1.073	–	1.43	4.81	3.5	2.00	1.20	6.44	4.3
2030 S 178	1.168	0.79	1.05	5.08	5.1				

Characteristics of two nearest missions towards asteroids Angelina (N64, E) and Pomona (N32, S) are given in table 5.

**Table 5.**

N type	$N_E^0$ [kW]	T [year]	$\varphi$ [degree]	$M_F^{ID}/M_F^{ST}$ [ton]	$V_J$ [km/s]	$M_{PL}^{ID}/M_{PL}^{ST}$ [ton]	$T_E$	$T_M$ [year]	$\Delta V$ [km/s]
64E	7.5	3.56	544	1.499	id	1.009	10.2011	6.22	4.0
				1.333	16.5	0.910			
				1.470	16.5+25	1.075			
32 S	7.5	3.05	452	1.330	id	0.906	01.2016	6.25	4.2
				1.239	16.5	0.797			
				1.313	16.5+25	0.886			

### Missions to Fortuna without assist of Mars.

Lately thanks to progress in space technologies and appearance of new materials it becomes possible to increase considerably the power of solar arrays without increasing of their size and mass. It seems to be realistic to increase the power

from the present 7-7.5 kW to 10 kW or even twice – up to 14 kW. The greater electric power will allow to rise the payload mass. In comparative with 7.5 kW the case of 10 kW of electric power and two types of electro-rocket engines gives an addition of 150 kg to the payload mass and rise it to almost sufficient volume of 845 kg (table 6).

**Table 6.**

$N_E^0$ [kW]	T [year]	$\varphi$ [degree]	$M_F^{ID}/M_F^{ST}$ [ton]	$V_J$ [km/s]	$M_{PL}^{ID}/M_{PL}^{ST}$ [ton]
10	2.86	405	1.317	id	0.891
			1.279	16.5+25	0.845

The increasing of electric power up to 14 kW will considerably enhance the new Space System and will make possible the straight flights from Earth to many asteroids of the Main Belt. In contrast to combined missions (with assist of Mars) the opportunity of straight flight to a definite objective appears each several years. Therefore several variants of missions to interesting from the scientific point of view asteroids of the Main Belt with start date at any given year may be found. Two types of asteroids – A and C – are of especial interest for investigation. Asteroids of C-type are mainly disposed in the far part of the Main Belt. There are still a lot of them (and of S-type) in the near part of the Belt, with apt sizes and lucky orbits (with eccentricity  $e < 0.15$ , inclination  $i < 10-15^\circ$ , large semiaxis  $a < 2.5$  a.u.). Energy expenses of missions to these asteroids are similar to Fortuna's.

Parameters of Fortuna mission with electric power 14 kW with dare start in 2006 year are given in table 7. Two variants of backward return to the Earth are presented. One – with backward start from Fortuna in 2010, with impulse o high

**Table 7.**

$N_E^0$ [kW]	T [year]	$\varphi$ [degree]	$M_F^{ID}/M_F^{ST}$ [ton]	$V_J$ [km/s]	$M_{PL}^{ID}/M_{PL}^{ST}$ [ton]	$T_S$	$T_\ominus$ [year]	$\Delta V$ [km/s]
14	2.86	405	1.452	id	1.053	09.2006	5	4.6
			1.377	25	0.963		6.12	3.5
			1.444	25+48.3	1.043			

thrust  $\Delta V = 4.6$  km/s and with full duration of mission  $T = 5$  years. Another – with start date in 2011,  $\Delta V = 3.5$  km/s and  $T = 6.12$  y. Two programs of stepped low thrust are considered. The first – with exhaust velocity  $V_J = 25$  km/s. The second gives better payload mass, but it supposes to use two types of electro-rocket engines – Russian SPT and German RIT-XX, and could be suggested for Joint Russian-European Project.

## RESUME.

The use of perturbation maneuver in the gravisphere of Mars or the use of enhanced solar arrays with electric power  $\approx 14$  kW will allow to realize missions with soil sample return from many asteroids of the Main Belt with the help of Space System worked out in the “Fobos-Ground” project.

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