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The Aster Project: Flight to a Near-Earth Asteroid

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Abstract—The information on the project being developed in Brazil for a flight to binary or triple near-Earth asteroid is presented. The project plans to launch a spacecraft into an orbit around the asteroid and to study the asteroid and its satellite within six months. Main attention is concentrated on the analysis of trajectories of flight to asteroids with both impulsive and low thrust in the period 2013–2020. For comparison, the characteristics of flights to the (45) Eugenia triple asteroid of the Main Belt are also given.

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1. PROJECT DESCRIPTION

Recently, natural satellites were discovered for many asteroids. There are such asteroids with one or two satellites also among the near-Earth asteroids, i.e., asteroids, whose orbits are close to the Earth's orbit. The investigation of binary or triple asteroid from close distance with the help of a spacecraft can be of considerable scientific interest. At present in Brazil, the development of the project for a flight to binary or triple near-Earth asteroid is started to perform investigations from an orbit around the asteroid. The project focuses on low-cost realization with the final spacecraft mass near the asteroid not exceeding 100 kg; search for the object among near-Earth asteroids is also dictated by the need to reduce the costs of the project.

This paper is devoted to the analysis of trajectories of flight to near-Earth asteroids within the framework of the Aster project. This project is at the very early stage of development, therefore, different (though not all) possible variants for its realization were considered. An analysis of flights to the triple asteroid of the Main Belt (45) Eugenia has been made. This large asteroid is of greater scientific interest than small near-Earth asteroids. However, of course, the flight to the Main Belt asteroid would have required larger expenditure of both fuel (propellant), and flight time. Larger distance of the Eugenia asteroid from the Sun and the Earth than in the case of near-Earth asteroid would require more powerful power supply and telecommunication that would also increase the costs of the project.

2. CANDIDATES AMONG ASTEROIDS

Primarily, several binary and triple near-Earth asteroids were selected for the preliminary analysis of transfer trajectories. The characteristics of these asteroids (candidates) are presented in Table 1, where the following designations are used: P is the orbital period, q, Q are the distances at perihelion and aphelion, respectively, i is the orbit inclination to the ecliptic, and D is diameter. The characteristics of the 45 Eugenia asteroid are also shown. Note that the diameters of most near-Earth asteroids are determined very approximately.

As seen from Table 1, large eccentricity and high inclination of the orbit of the (66391) 1999 KW4 asteroid would inevitably lead to unacceptably large value of the characteristic velocity required for the flight to the asteroid. Therefore, the 1999 KW4 asteroid was excluded from further analysis.

3. FLIGHTS WITH IMPULSIVE THRUST

As a parameter characterizing the admissibility of an asteroid from the point of view of the cost of the characteristic velocity for the flight to it, the sum of ΔV impulses of the launch from the low circular Earth's orbit and braking near the asteroid was accepted.[1] Val-

[1] Generally speaking, this formal summation is not quite correct, since the launch and braking are produced by different engines with different characteristics. However, if the additional acceleration with the help of the spacecraft engine is used near the Earth, this summation is possible; if the additional acceleration is not realized, this parameter can be considered as an approximate characteristic of flights.

Table 1. Characteristics of asteroids selected for analysis

Asteroid	*P*, years	*q*, AU	*Q*, AU	*i*, deg	*D*, km	Number of satellites	*D* of satellites, km
35107 1991 VH	1.2114	0.9730	1.2997	13.918	1.2	1	0.5
65803 Didymos	2.1086	1.0129	2.2758	3.408	0.8	1	0.15
66391 1999 KW4	0.5148	0.2001	1.0844	38.891	1.32	1	0.45
69230 Hermes	2.1290	0.6222	2.6877	6.068	0.4	1	0.4
136617 1994 CC	2.0984	0.9546	2.3234	4.684	0.7	2	>0.05, >0.05
153591 2001 SN263	2.7973	1.0370	2.9336	6.687	2	2	1 and 0.4
175706 1996 FG3	1.0824	0.6854	1.4231	1.990	1.4	1	0.43
45 Eugenia	4.49	2.497	2.943	6.610	214.6	2	13 and 6

Table 2. Characteristics of direct flights with impulsive thrust

Asteroid	Launch (month/year)	Arrival (month/year)	Flight duration, years	Launch ΔV, km/s	Braking ΔV, km/s	Total ΔV, km/s
35107 1991 VH	08/14	10/16	2.16	5.63	0.30	5.93
65803 Didymos	11/14	05/16	1.47	4.21	1.59	5.80
	11/16	06/18	1.56	4.34	1.27	5.61
	11/18	06/20	1.62	4.41	1.03	5.45
136617 1994 CC	07/13	06/15	1.92	5.01	0.72	5.73
	07/15	08/17	2.09	5.06	0.92	5.98
153591 2001 SN263	02/14	11/18	4.78	5.46	0.51	5.97

ues ΔV not exceeding 6 km/s were assumed acceptable.

As has been shown by the analysis, the direct flight with suitable values of ΔV is possible to asteroids 1991 VH, Didymos, 1999 CC, and 2001 SN263. The characteristics of these flights are given in Table 2.

As is seen from Table 2, the duration of the flight to the 2001 SN263 asteroid (4.78 years) is too large. The cause of this lies in the fact that a relatively acceptable value of ΔV is achieved only when the spacecraft executes a complete revolution around the Sun. Note that increasing duration of the flight leads to some decrease of the total impulse for other asteroids from Table 2 as well.

Another way to reduce the total impulse is to use a gravity assists near Venus and the Earth; these maneuvers also allow one to expand the list of asteroids achieved with low cost. The characteristics of flights with gravity assists near Venus or near Venus and the Earth are shown in Table 3.

The comparison of the data in Tables 2 and 3 shows that the gravity assists near Venus and the Earth (so-called maneuver VEGA,Venus and Earth Gravity Assist) somewhat reduces the total impulse of the flight to the Didymos and 2001 SN263 asteroids, in this case, the duration of the flight to the 2001 SN263 asteroid is significantly reduced in comparison with the direct flight. Venus swing by opens the possibility of flight to the 1996 FG3 asteroid with relatively low total impulse and flight duration. However, as seen from Table 3, flights with gravity assists to all considered near-Earth asteroids are possible only in 2020.

For the sake of comparison, Table 3 also shows the data of a flight to the Eugenia Main Belt asteroid with gravity assists near Venus and the Earth. In favorable (from the view of the project realization) launch date

Table 3. Characteristics of flights with gravity assists

Asteroid	Launch (month/year)	Venus flyby, (month/year)	Earth flyby, (month/year)	Arrival (month/year)	Flight duration, years	Launch ΔV, km/s	Braking ΔV, km/s	Total ΔV, km/s
65803 Didymos	03/20	10/20	12/22	08/23	3.41	4.10	0.82	4.92
153591 2001 SN263	05/20	10/20	03/22	01/23	2.74	3.85	1.65	5.50
175706 1996 FG3	02/20	06/20	–	06/21	1.33	3.97	1.27	5.24
45 Eugenia	05/15	10/15	07/16	12/17	2.65	3.65	5.22	8.87

and low starting impulse, a retroburn near this asteroid is too large for the low-cost project. Braking[2] with an acceptable consumption of propellant can be produced only by low thrust.

Note that the conversion of impulses into the final spacecraft mass has not yet been made, since this conversion depends on the used kick-stage and spacecraft's propulsion system. However, according to a rough estimation for the total impulse 5–6 km/s, the final spacecraft mass will be respectively 10–15% of the initial mass, including the kick-stage.

4. FLIGHTS WITH LOW THRUST

For flights with large (impulsive) thrust there is a discrete set of optimal launch dates and flight times with the possibility of small variations around optimal values. Flights with electrojet (low) thrust, in many cases, provide the possibility of arbitrary choice of the launch date with corresponding optimal flight duration (or choice of any flight duration with corresponding optimum launch date), in this case, the propellant consumption monotonically decreases with increasing flight duration. Therefore, an analysis of flights to asteroids was performed with the restrictions on the duration of heliocentric flight, namely, flights with the duration of 2 and 3 years for near-Earth asteroids and 3.5 years for Eugenia were considered.

In addition, the choice of launcher and the spacecraft mass characteristics depend strongly on the accepted scheme of acceleration near the Earth. Here, the following variants are possible:

—launching into a heliocentric trajectory by a kick-stage and the use of low thrust only for subsequent maneuvering on this trajectory and braking when approaching an asteroid;

—launching a spacecraft into low orbit of the Earth's satellite and its subsequent acceleration by onboard engine with low thrust; the duration of this acceleration can also be chosen rather arbitrarily by choosing the length of the thrust arcs in the perigee region (at larger length the acceleration time is reduced, but gravity losses will be increased and, accordingly, consumption of propellant will be increased too).

The intermediate variant is also possible: launching a spacecraft by impulsive thrust into an elliptical orbit around the Earth and then acceleration by low thrust. The altitude of apogee of the initial orbit can vary widely and should be selected based on specific conditions, the main of which is the capabilities of the launcher used.

An analysis of acceleration near the Earth was performed under the assumption that the acceleration is realized by low thrust from a low circular orbit of the Earth's satellite. The thrust was assumed to be tangential, the acceleration time was taken equal 8 months with an optimal choice of the lengths of the thrust arcs. The acceleration scheme is shown in Fig. 1.

The optimal value of velocity at infinity when inserting into the heliocentric trajectory depends on the concrete variant of the flight. As shown by numerical analysis, for variants considered this value is on average 0.8 km/s (with subsequent velocity increase required for the flight to the asteroid already on the heliocentric trajectory). The analysis of all accelera-

[2] The term "braking" may not seem entirely accurate, since, in many cases, it is necessary to increase the spacecraft velocity to encounter with an asteroid with zero velocity. However, if to consider the motion relative to the asteroid, a decrease of the spacecraft velocity occurs, i.e., braking.

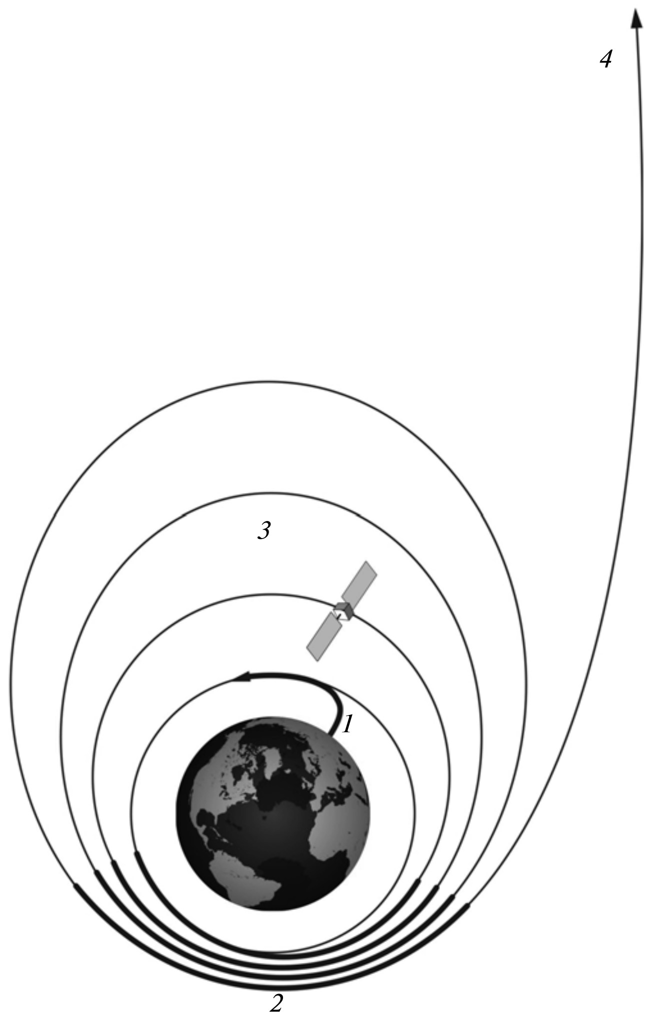

Fig. 1. The scheme of acceleration by low thrust near the Earth.
Spacecraft insertion into low circular orbit of the Earth's satellite (*1*); thrust arcs (*2*); coast arcs (*3*); approach to heliocentric trajectory (*4*).

tions with low thrust near the Earth was performed for this value of velocity at infinity.

Heliocentric flights were calculated for ideally controlled thrust of limited power (LP). However, the characteristics of existing low thrust engines are close to the thrust with constant outflow velocity and limited consumption of propellant (CEV). Therefore, the results obtained for LP, then were translated for the thrust with CEV according to a certain approximate procedure. Therefore, mass ratios given in Table 4 are approximate.

It was supposed to use solar panels as an power source for the spacecraft electric propulsion (EP). In accordance with this, the electrical power was assumed to be constant during ascend near the Earth and inversely proportional to the squared distance from the Sun at heliocentric trajectory.

To determine the ratio of the final mass of the spacecraft to its initial mass the following parameters were specified: the initial effective EP power (i.e., the power with accounting for the efficiency) is 7 W per 1 kg of spacecraft mass, the specific impulse is 2500 s. At initial spacecraft mass of 150 kg and the efficiency of 0.55 these values correspond to the effective power 1.05 kW, the total electrical power 1.91 kW, and the EP thrust 0.085 N. For example, the D-55 engine developed in TsNIIMash has approximately such characteristics.

Table 4 shows the characteristics of flights with a fixed duration to considered near-Earth asteroids and to Eugenia asteroid.

Table 4. Characteristics of flights with low thrust

Flight duration, years	Asteroid	Launch	Approach to heliocentric trajectory	Arrival	m/m_0
2	35107 1991 VH	06/17	02/18	02/20	0.63
	65803 Didymos	01/16	09/16	09/18	0.66
	69230 Hermes	04/14	12/14	12/16	0.58
	136617 1994 CC	10/15	06/16	06/18	0.66
	153591 2001 SN263	01/17	09/17	09/19	0.61
	175706 1996 FG3	10/17	06/18	06/20	0.67
3	35107 1991 VH	11/14	07/15	07/18	0.63
	65803 Didymos	02/15	10/15	10/18	0.68
	69230 Hermes	05/15	01/16	01/19	0.61
	136617 1994 CC	11/14	07/15	07/18	0.66
	153591 2001 SN263	04/16	12/16	12/19	0.62
	175706 1996 FG3	06/17	02/18	02/21	0.69
3.5	45 Eugenia	12/13	08/14	02/18	0.56

m_0 is the initial spacecraft mass, m is final spacecraft mass.

Table 4 shows not all the obtained results, but only some of them (as a rule, the results for the launch dates most suitable for the Aster project). The ratios of the final and initial masses given in Table 4 are approximate, since, as was noted above, for the heliocentric part of the trajectory these ratios were determined for LP and then converted for CEV by the approximate procedure.

Setting rigid restrictions on the flight duration has led to relatively narrow launch windows (i.e., intervals of launch dates, for which variations of the final mass are insignificant): for the results presented in Table 4, as well as for other obtained results these windows are one or two months. However, as was noted in the beginning of this section, for more flexible restrictions the flights with sufficiently high ratios of final and initial masses (of the same order as those listed in Table 4) are possible practically for any launch date.

5. SELECTION OF OBJECTS FOR THE PROJECT REALIZATION

Based on the performed analysis of flights to selected asteroids the preliminary selection of objects for the Aster project realization was made. These objects are triple asteroids (153591) 2001 SN263 (main object) and (136617) 1994 CC (reserve object). Figures 2 and 3 show the radar images of these asteroids and their satellites obtained by the Arecibo and Goldstone radio-telescopes. The advantage of these asteroids over others is the presence of two satellites for every asteroid, which makes them more interesting for the study. As seen from Tables 2 and 4, a flight to the 1994 SS asteroid requires less fuel or propellant than a flight to 2001 SN263, and the duration of the flight to 1994 SS with impulsive thrust is also considerably less. However, the 2001 SN263 asteroid and its satellites are considerably larger than the 1994 SS asteroid and its satellites; this is the reason why the 2001 SN263 aster-

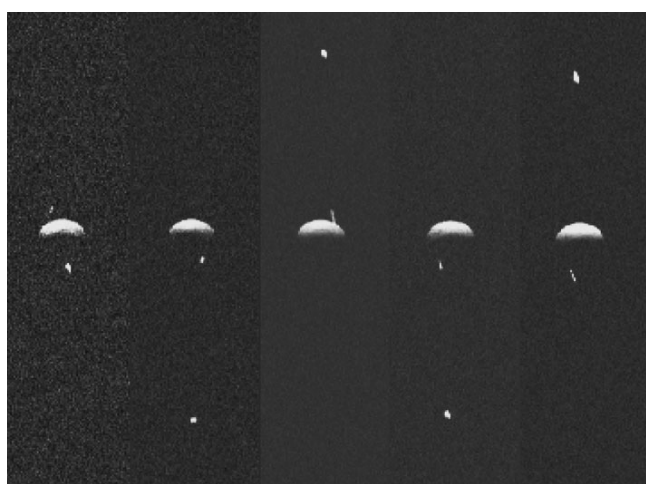

Fig. 2. Images of the 2001 SN 263 asteroid and its satellites obtained by the Arecibo radio-telescope.

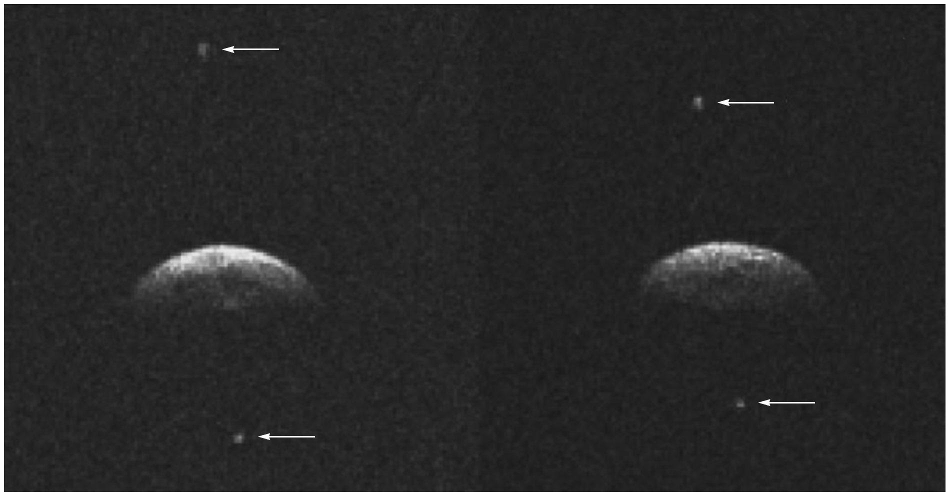

Fig. 3. Images of the 1994 CC asteroid and its satellites obtained by the Goldstone radio-telescope.

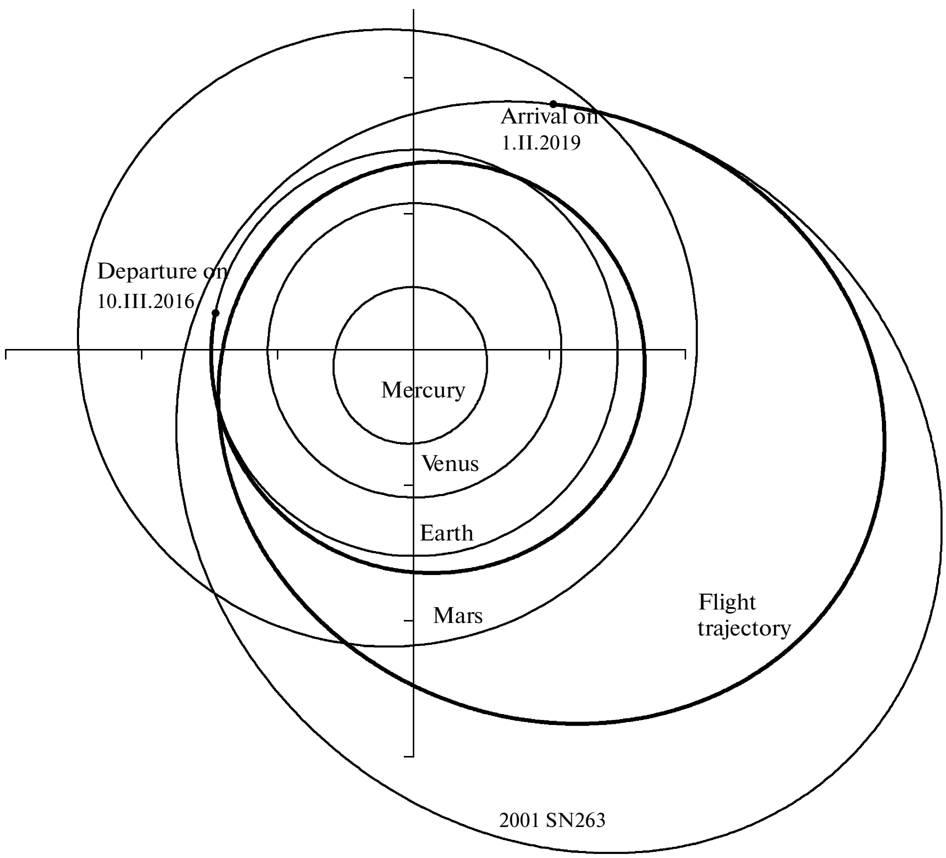

Fig. 4. Trajectory of flight to the 2001 SN 263 asteroid (the launch date is July 2015, $m/m_0 = 0.59$).

oid was selected as the primary object of the Aster project.

When analyzing flights considered in sections 2 and 3, the conditions of exploring the asteroids were not taken into account. These conditions primarily include the following: the spacecraft radio visibility from the Earth must be ensured and the distance from the Sun should not be too large during the time of

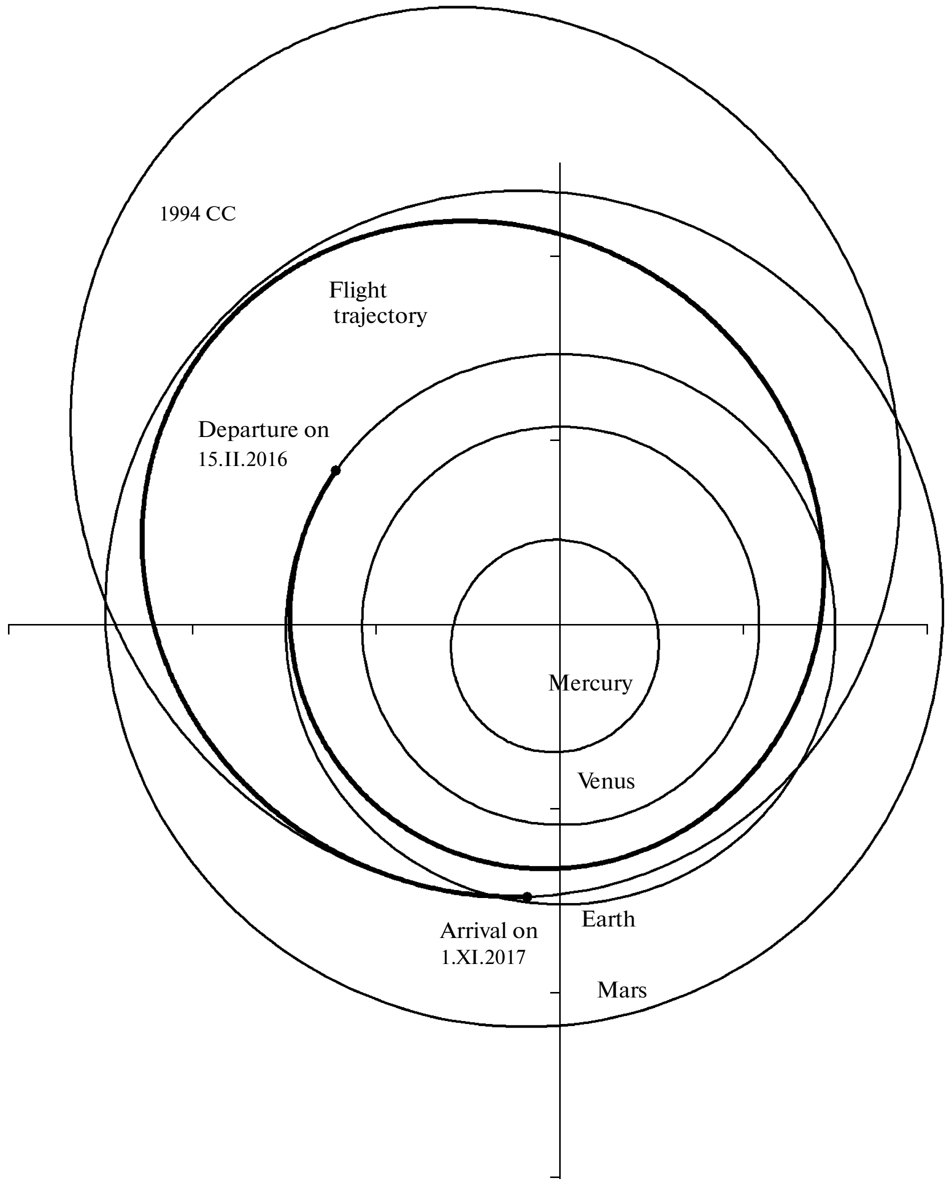

Fig. 5. Trajectory of flight to the 1994 CC asteroid (the launch date is June 2015, $m/m_0 = 0.61$).

investigation (we remind that for the Aster project this time was taken to be equal to six months). For the chosen 2001 SN263 and 1994 CC asteroids, the analysis was performed for flights with low thrust that provide favorable conditions for investigations. The characteristics and trajectories of these flight are shown in Figs. 4 and 5.

The time of launch to both asteroids (the middle of 2015) is extremely convenient for the Aster project, since it leaves five years for the preparation. Figures 4 and 5 show that encounter with both asteroids occur before their passage through perihelion and, thus, not too far distance from the Sun is achieved during the six months of asteroid investigation. Figures 6–8 show the distances of asteroids from the Sun and the Earth and the Sun–Earth–asteroid angles during the investigation.

Flights to each of two selected asteroids have the following advantages:

—the 2001 SN263 asteroid and its satellites are significantly larger than the 1994 CC asteroid and its satellites, the conditions of radio communication with the Earth during the investigations of the 2001 SN263 asteroid will be more favorable than for the 1994 CC;

—the flight to the 1994 CC asteroid requires less propellant at substantially shorter time of the flight.

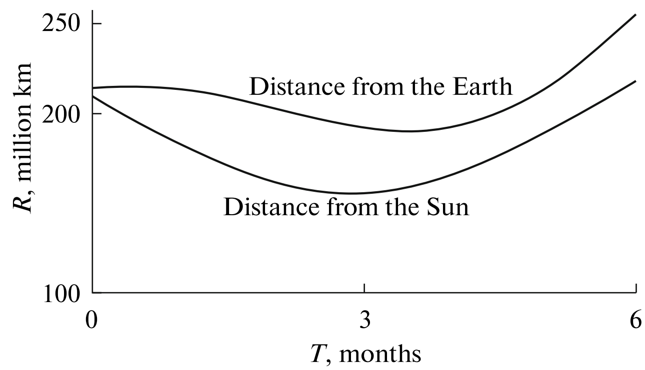

Fig. 6. The distance of the 2001 SN263 asteroid from the Sun and the Earth during investigations.

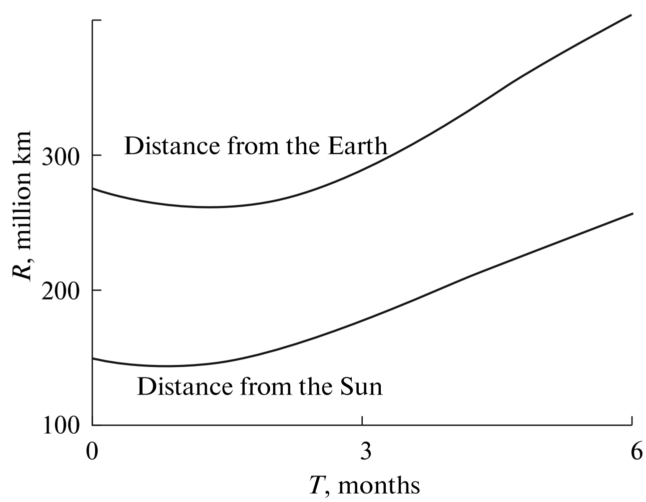

Fig. 7. The distance of the 1994 CC asteroid from the Sun and the Earth during investigations.

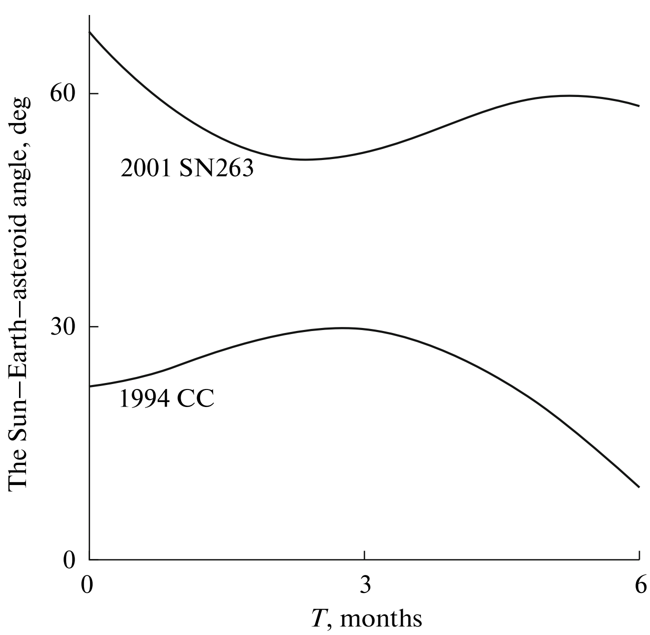

Fig. 8. The Sun–Earth–asteroid angles during investigations.

CONCLUSIONS

The above analysis demonstrated the possibility of realization of a flight to binary or triple near-Earth asteroid with low cost, as well as the possibility of a flight with low thrust to the (45) Eugenia Main Belt asteroid, however, in the latter case, both the propellant cost and the total project cost will slightly increase. For the flights with impulsive thrust to the near-Earth asteroids from Tables 2 and 3, in order to orbit a spacecraft with a mass of 100 kg around the asteroid, it will be necessary to launch into low orbit of the Earth satellite the kick-stage with the spacecraft of a total mass about one ton. The use of low thrust would allow one to restrict oneself by launching into an orbit around the Earth only a spacecraft with mass 150–170 kg with subsequent maneuvering using the onboard electric propulsion. This spacecraft can be launched as a piggyback payload or by superlight launcher.

However, the analysis, whose results are presented in this paper, is preliminary. At subsequent stages of the Aster project the more detailed analysis should be made, in particular, for flights with low thrust in the following areas.

(1) Estimation of the influence of the Earth's radiation belts on the spacecraft equipment at multiple passages through the belts at chosen scheme of acceleration (see Fig. 1) and elaboration of measures to reduce this influence. Such measures may be: high inclination of the initial spacecraft orbit; passing through the belts as soon as possible by way of rejecting coast arcs or using thrust arcs at apogee of the orbit in the initial stages of acceleration; the use of protection and redundancy for the most sensitive elements of the spacecraft equipment.

(2) Taking into account the Earth's shadow effect during acceleration and estimating possible additional costs of propellant (since electric propulsion system using solar energy cannot operate, when a spacecraft is in shadow, shadow thrust arcs are not optimal and the consumption of propellant can increase).

(3) More accurate determination of propellant consumption for the low-thrust heliocentric flight with CEV, with regard to possible new restrictions on the flight conditions.

(4) Determination of the stability zones of spacecraft orbit around the asteroid taking into account orbit perturbations by the asteroid satellites, estimation of the consumption of propellant for maneuvering near the asteroid.

The solution of these problems can change (increase) the estimates of both necessary expenditure of propellant and the dry spacecraft mass. If substantial increase in initial spacecraft mass is found to be unacceptable (for example, from the viewpoint of the project cost), the flight duration can be extended or another asteroid can be selected as the object of research (for example, Didymos or 1996 FG3, for which the consumption of propellant for flight is lower, see Table 4). One cannot also exclude that in the coming years new binary and triple near-Earth asteroids will be discovered, one of which can be more convenient object of exploration.