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Target selection and accessibility for rendezvous with a Near-Earth asteroid mission

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Abstract Mission to asteroids and comets has been the hot spot of deep space exploration in the new century. The choice of a suitable target, which involves both scientific value and technical feasibility, becomes a difficult task to accomplish due to limited energy and technology. The aim of this paper is to provide an approach to selecting a target and evaluating accessibility for rendezvous with a Near-Earth Asteroid mission, taking into account scientific value and engineering feasibility. Firstly, according to the orbital characteristics and physical properties of Near-Earth asteroids, we make a summary of some of the most frequent factors influencing the target selection of scientific significance. When selecting the target for a space mission, these factors can be regarded as the scientific motivations. Then in order to avoid the possibility that some high priority targets for science would be discarded due to requiring too high an energy budget by using a classical direct transfer strategy, we calculate the transfer trajectory for rendezvous with candidates by using the planetary swingby technique and the global optimal two-impulse method. Finally, through a comparison between the scientific relevance of each possible target and the corresponding estimate of energy needed for rendezvous missions, the ranking of some candidates is identified.

Keywords Target selection · Accessibility · Near-Earth asteroid

1 Introduction

Asteroid exploration missions attract many scientists' interest, because asteroids hold key clues to the understanding of the origin of our solar system and the formation of the planets. Near-Earth asteroids (NEAs) comprises a population subclass composed of objects that move in orbits, which may present a significant hazard

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to human civilization. These objects, whose dynamic characteristics allow close approaches to our planet, are gaining an increasing importance in many respects: science, technology and low cost (e.g. lower velocity increments, smaller launch vehicle, etc.). These celestial bodies are scientifically relevant as dynamically and physically evolved primitive bodies of the solar system, technologically challenging for their possible future exploitation as extraterrestrial resources.

To select a suitable target and analyze the accessibility of NEAs, some studies have been carried out in the past. Lau and Hulkower (1987) introduced a measure of accessibility, which is taken to be the global minimum total ΔV for a two-burn impulse rendezvous mission profile; and they presented a ranking of accessibility of NEAs. Perozzi, Rossi, & Valsecchi (2001) discussed the global characterization of the NEAs population on the basis of their dynamics, physical properties and flight dynamic considerations, investigated some basic targeting strategies for rendezvous and nodal and resonant fly missions to the NEAs, and presented a group of candidates, whose scientific motivations and some relevant orbital parameters were reported. A similar procedure was used by Binzel et al. (2004). They brought together an analysis of both Near-Earth Objects accessibility and preliminary assessments of their compositions. Using an H-plot analysis, they identified 234 currently known Near-Earth Objects that are accessible for rendezvous with a "best case" $\Delta V$of less than 7.0 km/s. In order to assess the accessibility of celestial bodies, the Hohmann strategy was used. These studies proved to be extremely useful in addressing the general topic of NEAs target selection. However, it is worthwhile noting that, in previous literature, the classical Hohmann transfer strategy and Lambert problem were used to estimate the minimum energy for rendezvous missions. Some targets in orbits similar to that of the Earth are easier to reach by using these classical transfer strategies. Yet, some high priority targets for science, in particular the large semi-major or eccentric ones, appear definitely out of reach given the present technological level when considering basic rendezvous missions (i.e. no gravity-assisted trajectories are foreseen). These high priority targets for science are extremely likely to be abandoned by a mission designer.

In what follows, we have primarily aimed this study at two aspects. Firstly, from the point of view of selecting scientifically interesting targets, we summarize some of the frequent factors influencing target selection on the basis of their physical properties and orbital characteristics. When selecting the target for a space mission, these factors can be regarded as the scientific motivations. Secondly, when analyzing the accessibility of targets, instead of the classical transfer strategies in previous literature, we calculate transfer trajectories to objects using the planetary swingby techniques. There are several reasons that lead us to adopt this approach. The main reason is that planetary swingby can reduce the total velocity increments and launch energy effectively. After calculating the transfer trajectory, an estimate of the energy needed for a "best case" mission scenario is presented. Finally, through a comparison between the scientific relevance of each possible target and the corresponding estimate of energy needed for rendezvous missions, the ranking of candidates is identified.

2 Target selection

NEAs are generally believed to be dynamically evolved fragments of main belt asteroids entering the inner solar system on chaotic orbits. Dynamical calculations show that the life spans for NEAs are typically a few million years, eventually meeting their doom by crashing into the Sun, being ejected from the solar system, or impacting a terrestrial world (Morbidelli, Bottke, Froeschlé, & Michel, 2002). With such short lifetimes, the NEAs observed today cannot be residual bodies that have continued orbiting among the inner planets since the beginning of the solar system. Understanding the sources and mechanisms of their evolution is one of the fundamental scientific goals for NEAs studies. The orbital characteristic, peculiar physical properties, in particular the taxonomic and mineralogical characterization of NEAs, may be extremely useful information for pinpointing the source regions of NEAs and their dynamical evolution. So it is very possible that the NEAs with peculiar orbital and physical properties become high scientific priority targets for exploration missions. The scientifically significant target will play an important role in understanding the origin and formation of the solar system and the planets. Of course, it is impossible and unwise to sum up all scientifically significant targets on the basis of our present lack of knowledge concerning their physical nature. Therefore, we will sum up some frequent factors influencing scientifically significant target selection on the basis of their physical properties and orbital characteristics. When selecting the target for a space mission, these factors can be regarded as the scientific motivations.

2.1 Physical properties

When analyzing and summarizing the frequent factors that influence scientifically significant target selection, we focus on those properties that give the best indication of the origin and dynamical evolution. We particularly focus on taxonomy, the relationships of NEAs to comets and ordinary-chondrite meteorites and the peculiar properties of NEAs such as shapes, rotations, optical properties and so on.

Taxonomic classes are from the system defined by Tholen (1984) and extended to include the additional designations developed by Bus (1999) and Bus and Binzel (2002). Almost all the taxonomic classes of main-belt asteroids are represented among classified NEAs, including the P-types and D-types most commonly found in the outer asteroid belt, between the Hilda and Trojan asteroid, or possibly among comet nuclei (Barucci, Cruikshank, Mottola, & Lazzarin, 2002; Weissman, Bottke, & Levison, 2002). Unique taxonomic classifications and mineralogical interpretations do show evidence for specific ties to main-belt sources. In particular, E-type asteroids appear both compositionally and dynamically related to the Hungaria region (high-inclination objects) of the inner asteroid belt (Gaffey et al., 1992). The C-type bodies would represent a sample of the pristine material characterizing the outer asteroid main belt. From the point of view of hazard-assessment and resource utilization, perhaps the objects of most practical interest are the M-types that may be highly metallic in composition (Tedesco & Gradie, 1987). V-type asteroids are also interesting, because they are widely believed to be fragments of the basaltic (pyroxene rich) surface of the large main belt asteroid 4 Vesta and are thought to be possible parent bodies of the Howardite Eucrite Diogenite meteorites (Binzel & Xu, 1993; Cruikshank, Tholen, Hartmann, Bell, & Brown, 1991; Migliorini et al., 1997; Thomas et al., 1997). So unique taxonomic classifications and mineralogical interpretations are the significant factor influencing scientifically significant target selection.

From the point of view of dynamical evolution, NEAs are widely believed to be dynamically evolved fragments of main belt asteroids entering the inner solar system. Taxonomic and mineralogic characterizations of NEAs also provide confident links to main-belt origins. Yet a fraction of NEAs might be composed by extinct cometary nuclei (Gladman et al., 1999). For instance, the taxonomic classification for 3200 Phaethon and 4015 Wilson–Harrington appears consistent with primitive solar system materials presumed to dominate in comets. D-type asteroids such as 3552 Don Quixote and 1997 SE5 do add to the list of NEAs having taxonomic characteristics that make them extinct comet candidates (Hicks, Buratti, Newburn, & Rabinowitz, 2000). These asteroids are well-known examples of this kind. So these objects, which might be cometary candidates, fragments of the main belt asteroid, meteor parent bodies etc., are potentially high value targets for science.

Though the taxonomic classes of NEAs show close similarities to main belt asteroids and the corresponding meteorites, the physical properties of NEAs may differ from those of main belt asteroids and meteorites. According to radar observations and the study of photometric light curves, some NEAs show the occurrence of highly elongated shapes, binary system, fast rotators and so on. These peculiar properties are valuable for the studies of origin and evolution of NEAs. For example, studies of amplitude brightness variation indicate that elongated shapes may provide some suggestions, when combined with dynamical and compositional factors, for discerning NEAs as having a cometary origin. Similarly, Binzel, Xu, Bus, and Bowell (1992) found that slower rotations might also indicate cometary candidates. Rotation and shape can help us understand these problems, which we focus on, notwithstanding the fact that rotation and shape alone are not sufficient by themselves to conclusively reveal a cometary origin for an individual NEA. Therefore, some peculiar properties such as exotic rotation station states, binary system, elongated shape, low albedo and so on, will also be significant factors influencing scientific target selection.

2.2 Orbital characteristics

The orbital characteristics of objects directly influence their accessibility for rendezvous mission, especially the semimajor axis a, eccentricity e and inclination i. A larger semimajor axis or inclination will make a challenge for rendezvous mission. On the other hand, NEAs moving on highly eccentric or inclined orbits have nontrivial dynamical implications. For example, most Amor asteroids are generally believed to be dynamically evolved fragments of main belt asteroids and short period comets. The inclination poses severe constraint on mission profiles, especially as far as rendezvous missions are concerned, in that out of plane maneuvers are in general rather demanding in terms of energy changes. According to the available estimates, there should be about more than half of NEAs having $i > 10°$. A few objects may reach 50° or more. These larger inclination objects always attract many scientists' attention because some of the larger inclination objects provide extremely useful information. For instance, among them, 1580 Betulia, whose inclination is 52.1°, D-class giant object 3552 Don Quixote asteroid, whose i is 30.8°, and 2,102 Tantalus ($i = 64.0°$) are well-known examples of this kind (Perozzi et al., 2001). Therefore, the orbital characteristics, which have nontrivial dynamic implications, are also an important factor, which impacts on target selection.

With the development and application of high sensitivity telescope techniques, the number of new asteroid discoveries increases dramatically with time. Scientific interest in the new individual targets is not very clear at present. So it is impossible to summarize all of the scientifically significant targets. On the other hand, a rather subjective parameter or finding a rigorous criterion to access the scientific relevance of an asteroid is also an elusive endeavor. Whereas, according to influencing factors mentioned above, the ‘‘scientific objects’’ can be easily updated and supplemented. In previous literature, Perozzi et al. (2001) presented the set of 60 scientifically significant targets. In this paper, we supplement 18 new candidates listed in Table 1. For each of them, the scientific motivations, and some relevant orbital and physical parameters are reported.

When selecting the target for a space mission, it usually happens that some objects are the ‘‘best candidates’’ from a scientific point of view, but they don’t satisfy the technical requirements. Therefore, when choosing a suitable target for exploration mission, the scientific and technical information about the target asteroid should be taken in account. In the next section, we will discuss the accessibility of NEAs.

3 Analyzing the accessibility of NEAs

We know the rendezvous missions would be in favor of investigating some object details such as composition, the morphology of its surface, shape, rotational properties, measuring its mass and obtaining indications of the internal structure and so on. The primary mission design consideration for a NEA rendezvous is usually the delta-V budget. This is a function of the velocity increment needed at the point of departure to insert the spacecraft into the transfer path and the change required to cancel the relative velocity between spacecraft and target at arrival. In previous literature, the direct transfer was used for analyzing the accessibility of NEAs. For example, the Hohmann transfer trajectories and the Lambert problem were used for giving a reference on the accessibility of NEAs (Binzel et al., 2004; Perozzi et al., 2001); the Gauss algorithm with boundary condition was used for calculating the transfer trajectory for NEAs (Christou, 2003). The global minimum total $\Delta V$for a two-impulse transfer was used to measure the accessibility (Helin, Hulkower, & Bender, 1984; Hulkower, Lau, & Bender, 1984; Lau et al., 1987). Asteroids in orbits similar to that of the Earth have better accessibility by using these classical transfer strategies. However, some high priority targets for science, in particular the large semimajor and eccentric ones, appear definitely out of reach at the present technological level when considering basic rendezvous missions. Therefore, in this paper, the planetary swingby techniques will be applied to generate transfer trajectories when measuring the accessibility of candidates. This approach can reduce the launch energy and total velocity increments and present a significant reference for the mission designer when selecting the maximized superposition between a scientifically significant and a technically feasible target for a space mission.

3.1 Transfer trajectory generation

The problem of finding the trajectory in space allowing a spacecraft to reach a given target can be solved in many different ways. For the purpose of this paper, namely to give a quick reference on the accessibility of NEAs, the approach based on Keplerian motion will suffice. In particular, the method of optimum two-impulsive transfer for preliminary interplanetary trajectory design (Hulkower et al., 1984) and the approach of Earth gravity-assist with deep-space maneuver (ΔV-EGA) (Farquhar, Dunham, & McAdams, 1995; Sim et al., 1997) will be used. ΔV-EGA refers

Table 1 New “scientific object” sample

Name	G	H^b (mag)	A^a	D^c (km)	T	R_p	Remark	P (days)	Q (AU)	G (deg)
(1981) Midas	AP	15.18	h	2.2	V;S	5.220	Possible Vest fragment; Radar observation	864.7	2.93	39.8
(3122) Florence	AM	14.20	0.20	2.5	E;S	2.3581	Possible chondrites; Fast rotator	859.4	2.52	22.2
(4486) Mithra	AP	15.60M	–	–	–	100	A nonprincipal axis rotation; Radar Observation	1195.1	3.66	3.0
(5604) 1992 FE	AT	16.40M	0.48	0.55	V	–	Possible Vesta fragment; Radar Observation	326.1	1.30	4.8
(10302) 1989 ML	AM	19.14R	m	0.6	X	19	Possible connection to the enstatite achondrite meteorites;	524.2	1.45	4.4
(14402) 1991 DB	AM	18.49R	0.14	0.60	C	2.266	Primitive main belt composition; Fast rotator	821.1	2.41	11.4
(16064) 1999 RH27	AM	16.07R	d	2.5	C	178.6	Primitive main belt composition; Slower rotator	1791.3	4.55	4.4
(25143) Itokawa	AP	18.61	0.32	0.36	S(IV)	12.132	Visited by Hayabusa spacecraft; Radar observation	556.5	1.69	1.6
(33342) 1998 WT24	AT	17.90M	0.43	0.42 × 0.33	E,Xe	3.6977	Possible connection to the enstatite achondrite meteorites; Radar observation	222.4	1.02	7.3
(38071) 1999 GU3	AM	19.60M	m	0.4	–	216	Very slow rotator; Radar Observation	1101.7	3.15	12.7
(53319) 1999 JM8	AP	15.15	m	3.3	X	136	Possible connection to the enstatite achondrite meteorites; Slow rotator; Radar Observation	1627.5	4.47	13.8
(65803) Didymos	AM	18.40M	–	–	Xk	2.26/11.9	Double lightcurve binary; Radar Observation; Possible connection to the enstatite achondrite meteorites	770.3	2.28	3.4
(66063) 1998 RO1	AT	18.10M	–	–	–	2.492/14.53	Double lightcurve binary; Radar Observation	360.3	1.70	22.7
(66391) 1999 KW4	AT	16.50M	m	1.6	S	2.765/17.45	Double lightcurve binary; Radar Observation	188.0	1.08	38.9
1990 OS	AP	20.00M	–	–	–	Hrs/18–24	Double lightcurve binary; Radar Observation	794.3	2.45	1.1
1996 FG3	AP	18.20M	m	1.6	C	3.594/16.14	Primitive main belt composition; Double lightcurve binary; Radar Observation	395.3	1.42	2.0
1997SE5	AM	14.8M	m	3.8	D;T	9.0583	Possible extinct comet candidates; possible Hilda and Trojan asteroid comet nuclei	2631.9	6.21	2.6
1999 SF10	AP	24.0	m	0.06		0.0411	Super fast rotators; Optical Observation	527.9	1.60	1.2

For each object, the NEA group (G), the absolute magnitude (H), the albedo (A), the diameter (D), the spectral type (T), the rotation period (R_p), the period of revolution (P), the aphelion distance (Q), and the orbital inclination (i) are listed. The Remarks on individual scientific relevance are also reported in the eighth column

[a] When albedo is not estimated through physical measurements, an approximation is assigned based on the taxonomic class. These assumed albedo are coded as follows: d for “dark” (0.006), m for “medium” (0.15), mh for “ medium high” (0.18), h for “high” (0.30). [b] “M” within this column indicates the value is from the Minor Planet Center (http:cfa-www.Harvard.edu/cfa/ps/mpc.html). [c] When diameter is not directly measured or determined through physical measurements. Information on the physical properties of our sample was retrieved from the European Asteroid Research Node internet database (http://earn.dlr.de/nea/database.htm)

to the use of a relatively small deep space maneuver to modify the excess hyperbolic velocity at a body. This maneuver, in conjunction with a gravity assist at the body, reduces the launch energy requirements and the total velocity increments for a mission.

3.1.1 Direct transfer

Asteroids in orbits similar to that of the Earth are easier to reach by using direct transfer profiles. So we adopt the optimum two-impulse transfer profiles. The method for numerically determining the optimum two-impulse transfer between two positions in two different heliocentric orbits was described (Hulkower et al., 1984). In this paper, it will not be reviewed. The optimum transfers obtained are ''time-open'' and the trajectories are computed using the patched-conic method. The minima are found by varying the semilatus rectum for each fixed pair of mean anomalies on the grid. The contours of minimum total $\Delta V$are plotted on axes of mean anomaly of the launch body at launch and mean anomaly of the target body at arrival. In the case of the 1998 KY26 Asteroid, the entire space of optimum rendezvous trajectories from Earth to target is displayed in Fig. 1 (It assumes that the Earth parking orbit is circular and of 200 km altitude). Through global search algorithms, the exact value of the global minimum total ΔV is found. The flight path is shown in Fig. 2.

Some of the ''scientifically significant'' targets in orbits similar to that of the Earth are calculated by using optimum two-impulse transfer profiles; and the trajectory parameters are displayed in Table 2 [The total $\Delta V$for two-impulse transfer consists of the launch from an Earth parking orbit (circular, 200 km altitude) ΔV_{L} and the impulse for rendezvous ΔV_{a}].

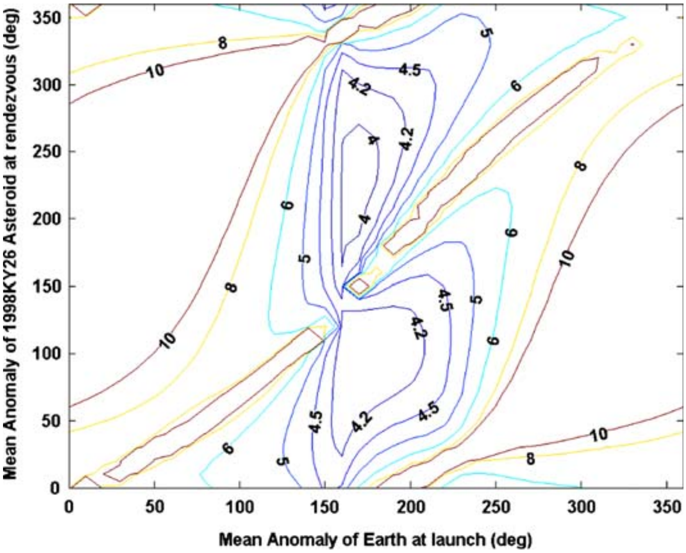

Fig. 1 Contours of minimum total ΔV for a two-impulse transfer trajectory to rendezvous with the 1998 KY26 asteroid

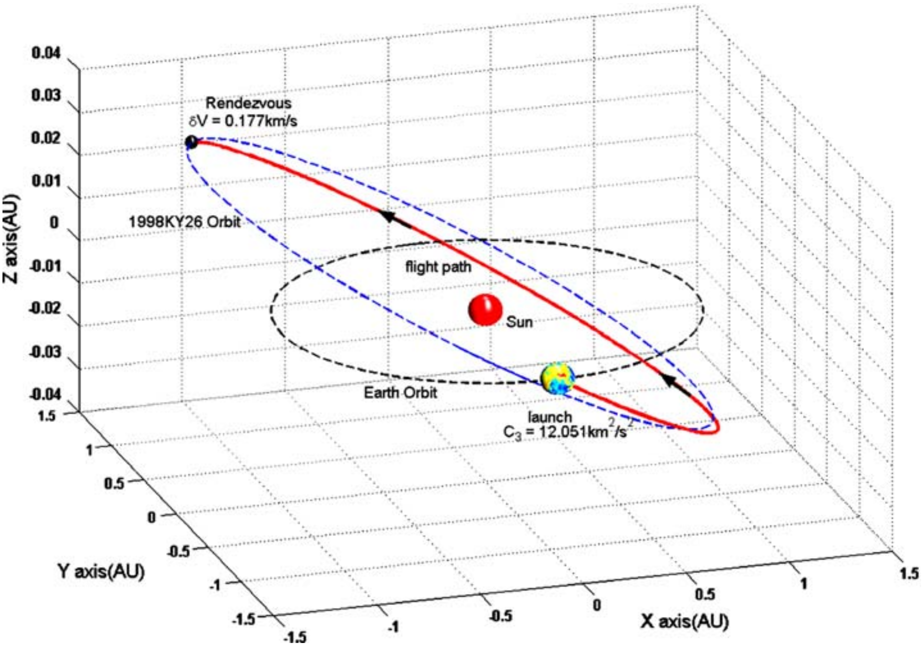

Fig. 2 The flight trajectory to rendezvous with the 1998 KY26 asteroid

Table 2 Global minimum two-impulsive trajectory parameters for rendezvous with target asteroid

Asteroid name	$\Delta V_{\mathrm{total}}$ (km/s)	M_{e} (deg)	M_{a} (deg)	T (days)
1998 KY26	3.916	169.151	224.908	338
1999 SF10	3.979	295.200	221.552	349
1998 SF36	4.267	144.281	157.365	235
4660 Nereus	4.454	20.083	115.808	208
1995 HM	5.013	133.059	103.137	193
3361 Orpheus	5.280	62.515	143.778	180

The total velocity increments ($\Delta V_{\mathrm{total}}$), Mean anomaly of Earth at launch (M_{e}), Mean anomaly of asteroid at arrival (M_{a}), time of flight (T) is listed respectively

3.1.2 Earth swingby transfer

Candidates moving on large eccentric or semimajor orbits require too much launch energy and total velocity increments for rendezvous mission by using the direct transfer strategies. In order to reduce further the dynamical requirements and avoid time-dependency, the gravity-assisted approach of Earth with deep-space maneuver (ΔV-EGA) will be used. First, it determines the two-impulse transfer trajectory from the Earth to asteroid. Then, through adjusting the mean anomaly of Earth at launch and matching the C_3, where C_3 defines the hyperbolic excess velocity squared V_{∞}^2 , it adds the ΔV-EGA to the beginning of the two-impulse transfer trajectory to reduce the required launch energy and the total ΔV for exploration missions. The flight path of the ΔV-EGA transfer profile is described by using the mean anomaly at launch M_{L}, the mean anomaly at swingby M_{s}, and the mean anomaly at rendezvous M_a, is the "time-open" or "ephemeris-free" solution. It is suitable for evaluating the accessibility of NEAs (Qiao, Cui, & Cui, 2006). The detailed design characteristics will not be reviewed.

The frequency of feasible opportunities is also an important factor when considering an asteroid for interplanetary mission. In previous literature, some studies have been carried out (Lau & Hulkower, 1987; Perozzi et al., 2001); in particular, Lau and Hulkower (1987) listed the frequency of feasible opportunities and average time for rendezvous with an asteroid. Although these frequencies were for the 21-years period, they were representative of what could be expected for these asteroids in general. Here, it is worthwhile noting that the ΔV-EGA allows extension of the classical two-impulse transfer strategy. The frequency of feasible opportunities for the ΔV-EGA strategy is larger than that of the two-impulse strategy, because there are several ΔV-EGA trajectories (such as 2:1 (±) ΔV-EGA etc.) that would correspond to a two-impulse trajectory.

In what follows, taking the 1627 Ivar asteroid, whose aphelion and inclination is 2.602 AU and 8.4° respectively, as an example, we will provide the ΔV-EGA strategy for analyzing its accessibility and predict the feasible opportunities from 2006 to 2016 years.

First, the two-impulse transfer trajectory of the global minimum total ΔV for a rendezvous mission is found. It assumes that the Earth parking orbit is circular and of 200 km altitude. The contour of minimum total ΔV for two-impulse transfer is shown in Fig. 3. The exact value of the global minimum total ΔV is found by using the global search algorithms. The flight path is shown in Fig. 4.

The mean anomaly of the Earth at launch for this two-impulse transfer trajectory can be obtained. It is regarded as the mean anomaly of the Earth at swingby for the ΔV-EGA transfer orbit. According to the characteristics of the Ivar asteroid orbit,

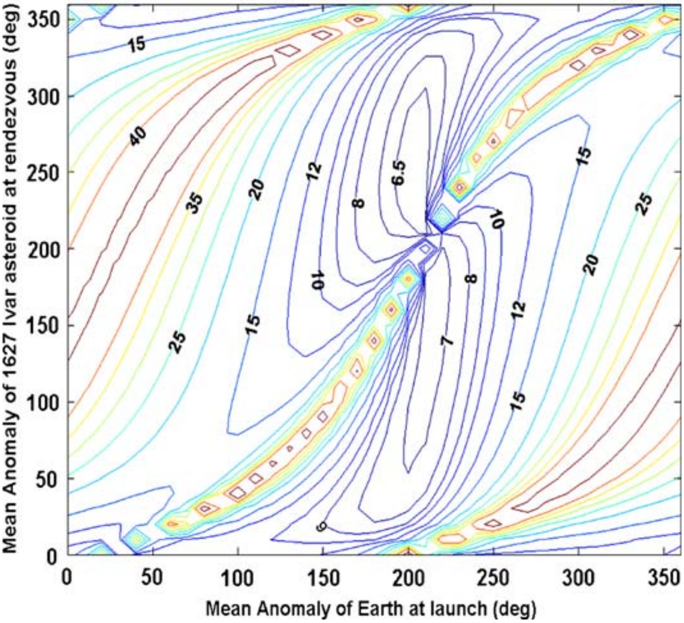

Fig. 3 Contours of minimum total ΔV for 1627 Ivar asteroid

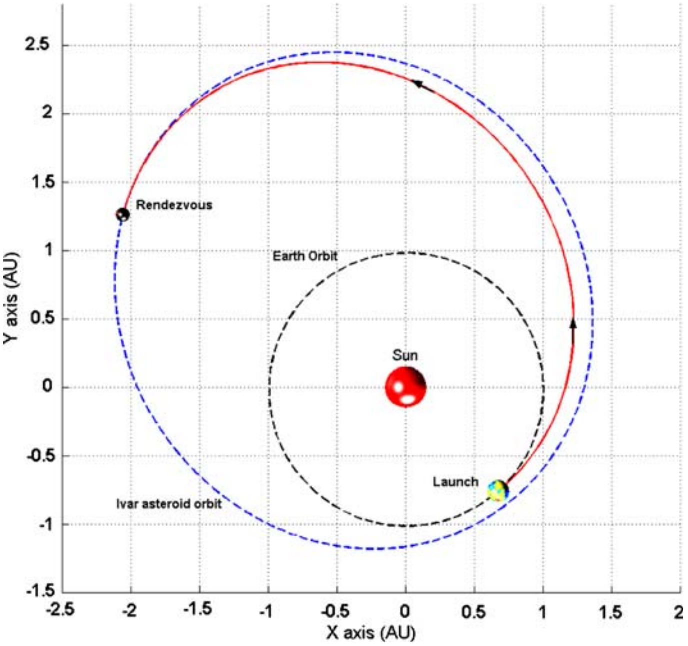

Fig. 4 Flight path of two-impulse transfer for Ivar asteroid

we select the 2:1 type for ΔV-EGA transfer (Qiao et al., 2006; Sims, Longuski, & Staugler, 1997). Then, we search a mean anomaly of the Earth at launch for the ΔV-EGA transfer orbit and propagate the orbit to the aphelion. The deep-space maneuver can be performed at aphelion; and the maneuver enables the Earth to be used as a gravity-assisted body. After swingby, the spacecraft flies to the target asteroid. The 2:1(±) ΔV-EGA transfer trajectory for rendezvous with Ivar asteroid is shown in Fig. 5 and Fig. 6, respectively.

The trajectory parameters of optimum two-impulse profiles and 2:1(±) ΔV-EGA profiles for rendezvous with the 1627 Ivar asteroid are listed in Table 3.

In Table 3, the M_L, M_s and M_a stand for Mean Anomaly of Earth at Launch, swingby and that of asteroid at arrival, respectively. For the swingby transfer, the total ΔV consists of the launch from an Earth parking orbit (circular, 200 km altitude) ΔV_L, the deep-space maneuver ΔV_m at aphelion and the impulse for rendezvous ΔV_a. The post-launch velocity increments ΔV_p is the sum of ΔV_m and ΔV_a. The C_3 and T are launch energy and time of flight, respectively. From Table 3, we can see that the total ΔV and launch energy C_3, compared with optimum two-impulse profiles, can be reduced 0.719 km/s and 24.237 km^2/s^2, respectively, by using 2:1(–) ΔV-EGA profile. In addition, we also see that one two-impulse trajectory allows extension of two ΔV-EGA trajectories. It also shows that the frequency of feasible opportunities for ΔV-EGA strategy will be more than that of a two-impulse strategy. According to Table 3, we can predict the feasible opportunities from 2006 to 2016 years. These feasible opportunities are listed in Table 4.

It should be noted that there is a difficulty in that the relative geometry of the celestial bodies and flight time needed is consistent with the ideal case because of the

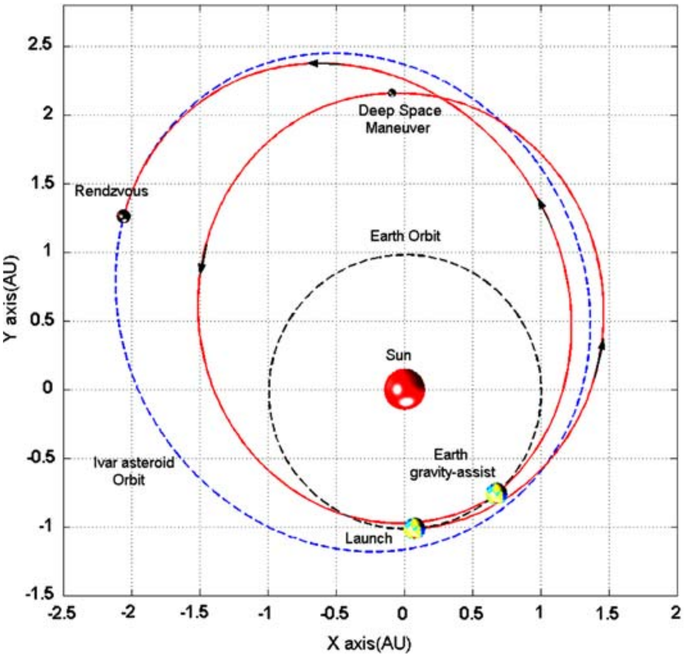

Fig. 5 The 2:1(+) ΔV-EGA transfer trajectory for Ivar

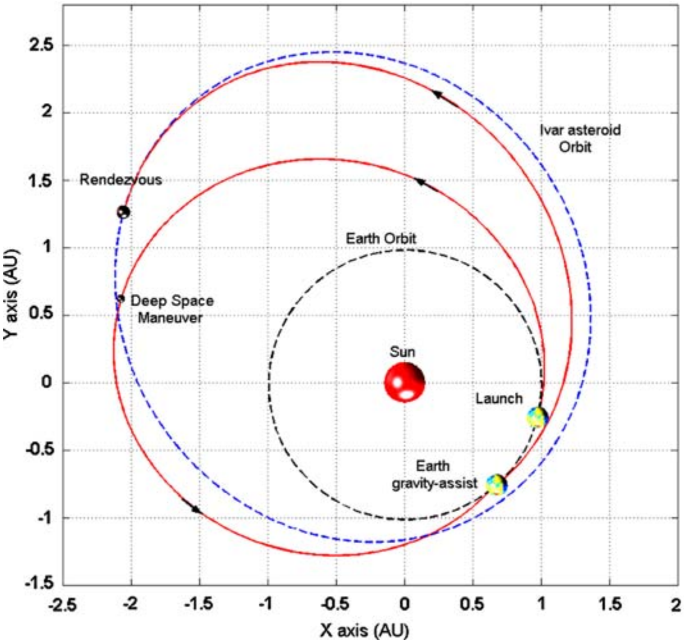

Fig. 6 The 2:1(–) ΔV-EGA transfer trajectory for Ivar asteroid

Table 3 A comparison of the optimum two-impulse and the 2:1 ΔV-EGA trajectory parameters for the Ivar asteroid rendezvous mission

	M_L (deg)	M_s (deg)	M_a (deg)	ΔV_{total} (km/s)	C_3 (km^2/s^2)	ΔV_p (km/s)	T (days)
Optimum two-impulse	206.894	–	236.556	6.108	50.593	0.796	564
2:1(+) ΔV-EGA	169.435	206.894	236.556	5.918	26.525	1.565	1,332
2:1(–) ΔV-EGA	242.463	206.894	236.556	5.389	26.356	1.043	1,258

ephemeris constraints. So the parameters of these opportunities have changed slightly. Although these opportunities are not optimal, they have a good initial value for a trajectory optimizer.

4 Results

The ΔV-EGA transfer trajectory technique can reduce launch energy requirements and total velocity increments at the cost of a deep-space maneuver and increasing flight time. This approach is suitable for a target with large-eccentricity or a large-semimajor. By using these classical two-impulse transfer strategies, some asteroids in orbits similar to that of the Earth are usually the easiest to reach [e.g. 1998 KY26 (a = 1.232 AU, e = 0.201), 1999 SF10 (a = 1.278 AU, e = 0.253), etc.]. However, to the object with large-eccentricity or large-semimajor [e.g. 4015 Wilson–Harrington (a = 4.258 AU, e = 0.623), 4179 Toutatis (a = 4.122 AU, e = 0.635), etc.], it requires so much launch energy and total ΔV that it appears to be out of reach (i.e. no gravity-assisted or low-thrust trajectories are foreseen). So in this case, the gravity-assisted strategy should be considered. In Table 5, we show the comparison of accessibility of some targets between using the two-impulse and gravity-assisted strategy. (It assumes that the Earth parking orbit is circular and of 200 km altitude).

In Table 5, the Q and e stand for the aphelion distance and eccentricity of asteroid, respectively. The total ΔV and launch energy C_3 required for rendezvous with large-eccentricity asteroids are reduced obviously by using the ΔV-EGA transfer technique, especially for candidates such as 4015 Wilson–Harrington (compared with the optimal two-impulse profile, the total ΔV and launch energy C_3 can be reduced by 1.168 km/s and 41.489 km^2/s^2, respectively), 4179 Toutatis (compared with the optimal two-impulse transfer, the total ΔV and launch energy of the ΔV-EGA transfer decreased by 17.32% and 60.36%, respectively), 6489 Golevka (the ΔV-EGA transfer profile has 1.053 km/s and 37.46 km^2/s^2 decrease in total ΔV and launch energy, respectively), and so on.

It is worthwhile noting that the classical two-impulse strategy was used for some asteroids in orbits similar to that of the Earth, when evaluating the accessibility of these objects. There are several reasons which lead us to adopt this approach. Perhaps the two most important ones are that (a) they display a very low launch energy and total ΔV: they have already appeared reasonably accessible by using the two-impulse transfer strategy; (b) if the ΔV-EGA strategy is used, it should need to add a heliocentric orbit with a period slightly greater than an integer number of years and a perihelion radius equal to the heliocentric orbit radius of Earth to the beginning of the two-impulse transfer trajectory. The heliocentric orbit not only

Table 4 The feasible opportunities for rendezvous with the Ivar asteroid from 2006 to 2016 years

	Launch date	Swingby date	Arrival date	M_e (deg)	M_s (deg)	M_a (deg)	ΔV_total (km/s)	C_3 (km^2/s^2)	T (days)
Two-impulse	Jul. 31, 2008	–	Feb. 06, 2010	206.75	–	236.68	6.144	49.48	555
	Aug. 1, 2013	–	Mar. 09, 2015	206.07	–	236.11	6.294	53.26	585
2:1(+) ΔV-EGA	Jun. 24, 2006	Jul. 31, 2008	Feb. 06, 2010	168.05	206.75	236.68	5.985	26.40	1,323
	Jun. 22, 2011	Aug. 1, 2013	Mar. 09, 2015	165.69	206.07	236.11	6.101	26.56	1,356
2:1(–) ΔV-EGA	Sep. 04, 2006	Jul. 31, 2008	Feb. 06, 2010	239.17	206.75	236.68	5.480	26.49	1,250
	Sep. 08, 2011	Aug. 1, 2013	Mar. 09, 2015	242.62	206.07	236.11	5.525	26.44	1,278

Table 5 A comparison of the accessibility of some targets between using the classic two-impulse strategy and the gravity-assisted strategy

Number/designation	Q (AU)	e	i (deg)	Global optimal two-impulse strategy		ΔV-EGA strategy	
				ΔV_{total} (km/s)	C_3 (km^2/s^2)	ΔV_{total} (km/s)	C_3 (km^2/s^2)
1998 KY26	**1.480**	**0.201**	**1.481**	**3.916**	**12.05**	–	–
1999 SF10	**1.602**	**0.253**	**1.226**	**3.979**	**12.50**	–	–
25143 Itokawa	**1.695**	**0.280**	**2.685**	**4.267**	**16.09**	–	–
4660 Nereus	**2.025**	**0.360**	**1.424**	**4.454**	**23.09**	–	–
3361 Orpheus	**1.599**	**0.323**	**2.683**	**5.280**	**19.45**	–	–
1627 Ivar	2.603	0.397	8.439	6.108	50.59	5.389	26.36
4015 Wilson–Harrington	4.285	0.623	2.783	6.799	67.12	5.632	25.63
4179 Toutatis	4.122	0.635	0.469	6.159	63.45	5.092	25.15
3551 Verenia	3.113	0.488	9.504	6.476	63.92	5.398	25.65
6489 Golevka	4.009	0.605	2.291	6.499	63.94	5.446	26.48

The bold characters indicate that these results were calculated by using the two-impulse strategy

needs some launch energy C_3 (e.g. for the 2:1 ΔV-EGA, it usually requires 25 ~ 26 km^2/s^2), but also adds a minor deep-space maneuver. So if the launch energy C_3 is less than 26 km^2/s^2 by using the classic two-impulse transfer, the ΔV-EGA strategy will not usually be considered.

5 Discussion and conclusions

When selecting the target for a space mission, besides potential scientific value, we need to take into account the technical feasibility of the mission. So the choice of a suitable target, which both involves scientific relevance and takes into account mission design considerations, is often a difficult task because of the limited launch energy and limited total energy budget at disposal. In this paper, we provide some approaches to resolving these problems. In this section, the ranking of accessibility for potential scientific value NEAs is completed. These scientifically significant targets include 60 objects (Perozzi et al., 2001) and 18 objects are listed in Table 1. A summary of these results is presented in Table 6.

In Table 6, we consider some of the most frequent constraints for mission design: (1) Total velocity increments ΔV_{total}: this is a crucial parameter influencing the feasibility of a mission; this condition should ensure that the mission could be accomplished with a small or medium class launch vehicle; (2) Launch energy C_3: the launch energy has impact on the choice of rocket, with the current trend towards cheaper missions, the rocket may often represent the largest cost faced by a mission designer; therefore reducing the launch energy and choosing the smallest possible launcher able to accomplish a desired mission becomes crucial; (3) Post-launch velocity increments ΔV_{p}: after the spacecraft escapes into interplanetary space by supporting an upper stage of the rocket, the post-launch velocity increments will be offered by the spacecraft on-board propulsion system; so the post-launch velocity increments have an impact on the technical characteristics of the on-board propulsion systems, the dimensioning of the spacecraft and payload and the launch vehicle;

Table 6 The ranking of accessibility for potential scientific value NEAs

Rank	Asteroid name	ΔV_{total} (km/s)	ΔV_{pl} (km/s)	C_3 (km^2/s^2)	M_e (deg)	M_s (deg)	M_a (deg)	T (days)	A	D (km)	TA	P (h)
1	1998 KY26	3.916	0.178	12.051	169.151	–	224.908	338	D	0.04	CP	0.178
2	1999 SF10	3.979	0.221	12.501	295.200	–	221.552	349	m	0.06	–	0.041
3	(25143) Itokawa	4.267	0.347	16.090	144.281	–	157.365	235	0.32	0.36	S(IV)	12.15
4	(10302) 1989 ML	4.277	0.517	12.074	182.528	–	172.404	243	m	0.6	X	19.0
5	(4660) Nereus	4.437	0.227	23.088	19.991	–	114.708	206	d	1.2	C	15.1
6	(35107) 1991 VH	4.891	0.550	26.226	257.541	218.056	162.255	919	mh	1.4	Sk	2.624
7	(7341) 1991 VK	4.968	0.664	25.344	39.224	11.656	205.985	1,235	mh	1.4	Sq	4.209
8	1990 OS	4.995	0.667	25.919	282.235	259.000	213.318	1,209	–	–	–	Hrs/18-24
9	(33342) 1998 WT24	4.995	0.699	25.148	21.457	340.306	346.433	773	0.42	0.5	E	3.697
10	1995 HM	5.013	1.030	17.726	133.059	–	103.137	193	m	0.11		1.62
11	(4179) Toutatis	5.091	0.794	25.148	338.483	297.865	247.351	1,718	0.13	2.8	S,Sq	129.8
12	(3288) Seleucus	5.179	0.828	26.478	142.035	111.459	230.066	1,336	0.17	2.8	S	75
13	(3908) Nyx	5.193	0.886	25.408	316.129	289.471	294.806	1,454	0.23	0.9	U	4.426
14	(65803) Didymos	5.224	0.916	25.432	314.416	299.473	296.506	1,314	–	–	Xk	2.26/11.9
15	(3361) Orpheus	5.280	1.223	19.454	62.515	–	143.778	180	m	0.5		3.58
16	(8034) 1992 LR	5.339	0.987	26.489	214.048	192.479	66.977	880	mh	0.8	S	3.638
17	(1627) Ivar	5.389	1.043	26.356	242.463	206.894	236.556	1,258	0.26	6.9	S	4.797
18	(3551) Verenia	5.398	1.082	25.645	300.329	257.640	121.743	1,062	0.53	0.9	V	4.93
19	(6489) Golevka	5.443	1.092	26.478	217.758	176.002	53.731	906	0.63	0.35	Q	6.026
20	(433) Eros	5.543	1.236	25.399	43.212	21.697	180.799	1,006	0.21	23.6	S(IV)	5.27
21	(3352) McAuliffe	5.551	1.251	25.261	32.631	12.247	126.685	1,027	0.18	2.4	S	3
22	(4015)Wilson–Harrington	5.632	1.316	25.630	301.287	257.175	311.274	2,015	0.05	2	CF	3.556
23	(887) Alinda	5.634	1.328	25.384	42.171	2.898	230.683	1,563	0.23	4.2	S	73.9
24	(13651) 1997 BR	5.668	1.329	26.199	260.177	195.532	212.473	960	mh	0.9	S	33.64
25	(38071) 1999 GU3	5.894	1.543	26.459	136.524	96.698	135.293	1,106	m	0.4	–	216
26	(31345) 1998 PG	5.948	1.643	25.370	318.901	289.069	255.098	1,328	0.16	0.9	Q	2.516
27	(3102) Krok	6.039	1.706	26.019	275.033	237.219	267.242	1,433	m	1.6	S	147.8
28	(1685) Toro	6.051	1.742	25.468	47.999	353.779	222.381	1,015	0.31	3	S	10.19
29	1994 AW1	6.054	1.714	26.211	259.060	188.576	133.442	852	mh	1.0	Sa	2.519
30	(4486) Mithra	6.068	1.715	26.528	182.982	145.910	222.860	1,510	–	–	–	100
31	1997 SE5	6.085	1.761	25.824	288.712	236.697	65.722	1,145	m	3.8	D,T	9.058
32	(1620) Geographos	6.148	1.831	25.665	299.047	234.979	346.522	1,055	0.19	5	S	5.223
33	1996 FG3	6.246	2.590	9.694	199.258	–	184.161	273	m	1.6	C	3.594/16.14

Table 6 continued

Rank	Asteroid name	$\Delta V_{\mathrm{total}}$ (km/s)	ΔV_{pl} (km/s)	C_3 (km^2/s^2)	M_{e} (deg)	M_{s} (deg)	M_{a} (deg)	T (days)	A	D (km)	TA	P (h)
34	(2100)Ra-Shalom	6.353	2.037	25.620	301.955	250.607	0.040	789	0.13	2.5	Xc	17.79
35	(6178) 1986 DA	6.359	2.010	26.423	128.523	87.532	53.384	936	0.14	2.3	M	3.58
36	(2063) Bacchus	6.382	2.078	25.295	324.596	290.525	189.458	996	mh	1.2	Sq	14.90
37	(7753) 1988 XB	6.420	2.104	25.651	299.964	274.577	114.329	916	d	1.0	B	–
38	(53319) 1999 JM8	6.426	2.082	26.290	250.774	201.122	247.456	1,801	m	3.3	X	137
39	(16064) 1999 RH27	6.553	2.255	25.176	24.588	346.596	308.032	1,908	d	2.5	C	178.6
40	(3671) Dionysus	6.625	2.273	26.477	218.066	174.159	91.735	1,009	0.16	1.5/27.7	Cb	2.705
41	(14402) 1991 DB	6.649	2.307	26.256	105.534	67.438	46.875	832	0.14	0.6	C	2.266
42	(35396)1997 XF11	6.702	2.368	26.052	272.534	242.846	114.004	903	–	2.8	Xk	3.259
43	(8201) 1994 AH2	6.899	2.556	26.311	111.638	47.977	185.189	1,515	m	2.2	O	23.95
44	(2201) Oljato	6.911	2.563	26.402	124.683	86.210	117.499	1,107	0.24	2.1	Sq	24
45	(3103) Eger	7.144	2.818	25.872	285.497	210.914	29.457	763	0.53	2.5	E	5.709
46	(3122) Florence	7.164	2.859	25.350	320.348	238.876	231.855	1,203	0.20	2.5	E;S	2.3581
47	(1917) Cuyo	7.181	2.888	25.113	343.140	265.655	214.005	1,332	mh	5.2	Sl	2.691
48	(5751) Zao	7.234	2.916	25.716	64.306	29.523	109.627	1,029	m	3.5	X	21.7
49	(6611) 1993 VW	7.448	3.097	26.523	193.569	115.568	165.779	971	h	1.2	V	–
50	(4769) Castalia	7.583	3.278	25.357	319.834	235.715	326.680	865	m	1.4	–	4.086
51	(1862) Apollo	7.642	3.343	25.194	26.433	303.990	188.091	937	0.26	1.4	Q	3.065
52	(69230) Hermes	7.699	3.365	26.085	89.993	54.400	105.184	932	–	2.1	S	13.89
53	(4954) Eric	7.734	3.439	25.119	342.236	261.651	185.800	1,179	mh	9.5	S	12.05
54	(2101) Adonis	7.875	3.568	25.396	316.970	279.167	204.336	1,369	–	1.2	–	–
55	(5604) 1992 FE	7.938	3.588	26.462	222.475	175.717	4.862	923	0.48	0.55	V	–
56	(66391) 1999 KW4	7.951	2.701	48.990	231.689	141.583	9.602	942	m	1.6	S	2.61
57	(4055) Magellan	7.973	3.669	25.343	320.902	244.246	266.749	1,153	0.24	3	V	7.475
58	1989 VA	8.104	3.808	25.188	25.892	304.934	187.610	747	mh	0.8	Sq	2.514
59	(1865) Cerberus	8.433	4.080	26.519	162.334	120.682	188.411	916	0.26	1	S	6.810
60	(7888) 1993 UC	8.605	3.348	49.164	145.350	69.543	188.747	1,616	mh	3.1	S	2.340
61	(4197) 1982 TA	8.729	4.380	26.419	127.954	63.212	86.280	985	0.33	1.7	Sq	3.54
62	(3691) Bede	8.777	4.432	26.321	112.899	75.584	80.406	918	m	3.6	Xc	226.8
63	(3554) Amun	8.856	4.542	25.557	306.041	258.886	179.201	897	0.17	2.1	M	2.530
64	1996 JA1	9.459	4.208	49.008	230.190	143.033	169.117	1,675	0.30	0.2	V	5.227
65	(5143) Heracles	9.462	5.111	26.485	144.469	103.424	106.820	999	mh	5.0	O	15.8
66	(2212) Hephaistos	9.519	5.166	26.509	204.139	157.386	104.918	1,086	mh	3.3	SG	20

Table 6 continued

Rank	Asteroid name	$\Delta V_{\mathrm{total}}$ (km/s)	ΔV_{pl} (km/s)	C_3 (km^2/s^2)	M_{e} (deg)	M_{s} (deg)	M_{a} (deg)	T (days)	A	D (km)	TA	P (h)
67	(1036) Ganymed	9.613	4.444	46.860	23.734	295.511	140.251	1,374	0.17	38.5	S(IV)	10.31
68	(6053) 1993 BW3	9.782	4.599	47.257	314.266	227.049	229.780	1,449	0.18	3.1	Sq	2.573
69	(3753)Cruithne	9.889	5.570	25.698	63.038	9.696	170.224	955	mh	3.3	Q	27.44
70	(1864) Daedalus	9.910	5.619	25.067	352.607	265.026	221.812	1,122	mh	3.1	Sr	8.57
71	(1866) Sisyphus	10.214	5.012	47.806	68.839	321.747	253.141	1,375	0.14	8.9	S	2.400
72	(3552)DonQuixote	10.223	5.883	26.097	269.053	215.812	311.788	2728	0.02	18.7	D	7
73	(1981) Midas	10.556	5.295	49.289	189.699	75.050	329.021	1,467	h	2.2	S;V	5.22
74	(1566) Icarus	11.249	6.045	47.794	291.651	166.286	119.717	1,066	0.33	1.3	SU,Q	2.273
75	(1580) Betulia	11.440	6.191	48.622	254.960	133.649	301.256	1,600	0.17	3.9	C	6.132
76	(3200) Phaethon	12.801	7.556	48.762	112.810	340.905	187.352	1,079	0.11	5.1	B,F	3.57
77	(66063) 1998 RO1	12.902	8.551	26.469	139.315	91.520	186.220	912	–	1.6	–	16.9
78	(2102) Tantalus	13.768	8.517	48.994	128.614	354.527	6.939	1,117	m	3.3	Q	2.391

For each object, the total velocity increments ($\Delta V_{\mathrm{total}}$) for rendezvous mission, the post-launch velocity increments ΔV_{p}, launch energy at Earth C_3, Mean Anomaly of Earth at Launch (M_{e}), Mean Anomaly of Earth at swingby (M_{s}), Mean Anomaly of asteroid at arrival (M_{a}), time of flight (T), the albedo of asteroid (A), the diameter of asteroid (D), the spectral type of asteroid (TA), the period of rotation (P) are listed

(4) Physical property: the physical properties of a NEA influence its scientific value from a mission operational aspect and its overall engineering feasibility for a rendezvous mission. For example, NEAs belonging to specific taxonomic classes may be preferred as mission targets for scientific reasons. The size of the asteroid combined with its albedo and rotation rates have impact on the navigation system of the spacecraft. Some parameters about these constraints are also listed in Table 6.

We know that the NEAR mission (Farquhar et al., 1995) showed the actual feasibility of a highly sophisticated interplanetary mission with a first-class scientific target, at a reasonably low cost and spacecraft and operation complexity. However, the choice of a suitable target is a difficult task, because according to NASA instructions, Discovery mission must have well-focused scientific objectives as well as strict limits on project costs and development time. In addition, Discovery missions must use launch vehicles of the Delta class or smaller. According to these requirements, some constraints were determined. For example, the total ΔV requirements should be less than 6.0 km/s and the post-launch ΔV requirements should not exceed 2.00 km/s and so on. Considering these conditions, we found that 4 candidates out of 60's scientifically significant targets can satisfy them on the basis of Perozzi et al. (2001) estimates. However, by using the Earth swingby technique, 19 candidates can satisfy with these constraints, in particular several high priority targets for science such as 4015 Wilson–Harrington, 4179 Toutatis, 3551 Verenia, 6489 Golevka and 887 Alinda. In what follows, these scientifically relevant asteroids as listed in Table 6 can be grouped for discussion according to the most important topics that a space mission could help investigate.

We know the difficulties involved in trying to reach cometary candidates, because their dynamical characteristics have already been described. Among these strong cometary candidates, 4015 Wilson–Harrington appears to have reasonable accessibility in that the total velocity increments ($\Delta V_{\text{total}} = 5.623$ km/s) and post-launch velocity increments ($\Delta V_{\text{p}} = 1.316$ km/s) are not only lower than other cometary candidates, but can also satisfy some of the requirements of the NEAR mission.

Meteor parent bodies are interesting because they possibly hold primitive information about planetary evolution. Among these candidates, 6178 1986 DA, that is generally believed to be the iron meteorites parent body, requires a high total velocity for rendezvous mission ($\Delta V_{\text{total}} = 9.1$ km/s, Perozzi et al., 2001); yet by using Earth swingby profiles, the ΔV_{total} is reduced to 6.355 km/s. Giant NEAs are not particularly accessible for rendezvous, apart from 433 Eros, because of the high inclinations involved and the long revolution periods.

Some objects that have some peculiar properties such as exotic rotation station states, a binary system, elongated shape, low albedo and so on, are also regarded as primary targets. Among them, asteroid 4179 Toutatis, extensively imaged by radar and possibly in a peculiar rotation state, exhibits some favorable accessibility. The total velocity increments and post-launch velocity increments required for rendezvous mission are 5.092 and 0.796 km/s, respectively. In addition, 887 Alinda, 3288 Seleucus, 1995 HM, 1997 BR, 1998 KY26 that have exotic rotation station states, also show extremely favorable accessibility.

V-type objects are also regarded as primary targets, because of their supposed origin as fragments of the basaltic surface of Vesta. The 3361 Orpheus, whose period is 1.33 years and inclination is 2.68° shows the lower rendezvous energy requirements ($\Delta V_{\text{total}} = 5.280$ km/s, $\Delta V_{\text{p}} = 1.223$ km/s). For the others the situation is worsened by the distant aphelia, which in the case of 6489 Golevka may exceed

4 AU, is also found. Although the distant aphelia of 6489 Golevka exceeds 4 AU, the asteroid is approachable because of the low total velocity increments ($\Delta V_{\text{total}} = 5.447$ km/s) and post-launch velocity increments ($\Delta V_{\text{p}} = 1.095$ km/s).

It should, however, be kept in mind that these considerations refer only to the basic transfer trajectory. If multiple planetary swingby will be foreseen in the mission design process, even the most difficult cases may become feasible; however, the two-impulse and Earth swingby transfer trajectory should be computed starting from the actual transfer orbit found.

In conclusion, the purpose of this paper was to give a basic reference for the target selection and the analysis of the accessibility of a rendezvous mission. Some frequent factors influencing target selection were summarized. According to these factors, more and more potentially scientifically valuable asteroids will be found and updated. When measuring the accessibility of candidates, the planetary swingby techniques have been applied to the transfer path generation. It can effectively reduce the launch energy and total velocity increments for rendezvous mission and avoid the possibility that some high priority targets for science will be discarded due to requiring too much launch energy and total velocity increments.

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