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NEAR-EARTH ASTEROIDS ACCESSIBLE TO HUMAN EXPLORATION WITH HIGH-POWER ELECTRIC PROPULSION

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The diverse physical and orbital characteristics of near-Earth asteroids provide progressive stepping stones on a flexible path to Mars. Beginning with cislunar exploration capability, the variety of accessible asteroid targets steadily increases as technology is developed for eventual missions to Mars. Noting the potential for solar electric propulsion to dramatically reduce launch mass for Mars exploration, we apply this technology to expand the range of candidate asteroid missions. The variety of mission options offers flexibility to adapt to shifting exploration objectives and development schedules. A robust and efficient exploration program emerges where a potential mission is available once per year (on average) with technology levels that span cislunar to Mars-orbital capabilities. Examples range from a six-month mission that encounters a 10-m object with 65 kW to a two-year mission that reaches a 2-km asteroid with a 350-kW system.

INTRODUCTION

In the wake of the schedule and budgetary woes that led to the cancellation of the Constellation Moon program, the exploration of near-Earth asteroids (NEAs) has been promoted as a more realizable and affordable target to initiate deep space exploration with astronauts.[1,2] Central to the utility of NEAs in a progressive exploration program is their efficacy to span a path as literal stepping stones between cislunar excursions and the eventual human exploration of Mars.[3–8] In the search for initial mission targets, several studies have demonstrated that the Constellation paradigm (specifically short duration habitats propelled by massive propulsion systems that require Saturn V-class launchers) limits the set of "attractive" missions to sporadically spaced launches encountering a few dozen of the easiest to reach objects.[9–16] These targets tend to be relatively small (< 100 m) with uncertain orbits, which introduces significant issues for both public engagement and mission design. Noting the paucity of exploration targets possible with Constellation capability, many in the NEA community have called for a dedicated NEA survey in order to discover a new set of easily accessible targets.[17] Such tactics arise from a desire to find NEAs accessible within the capability of architectures like Constellation or Apollo that were originally formulated for cislunar exploration. By only pursuing cislunar architectures, the exploration program would be limited to the small fraction of asteroids with Earth-like orbits.

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After the publication of the Augustine Commission,[1] we became interested in how technologies useful for Mars exploration could pertain to NEAs, and how these technologies map back to cislunar missions. Such strategic technologies could open the exploration program to a larger fraction of asteroids that span out to Mars. Noting the dramatic reduction in injected mass to low-Earth orbit (IMLEO) enabled by solar electric propulsion (SEP) for Mars surface missions,[18–21] we sought applications that would bring exploration capability to NEAs as well. The underlying premise is that the investment in a high-power SEP stage[22] potentially reduces overall program cost by decreasing the number of required launches or by allowing the use of more economical launch vehicles. We found that power levels comparable to the International Space Station (the ISS arrays can produce up to 260 kW[23]) enabled several 1–1.5 year NEA missions to relatively large (>300 m) targets with well characterized orbits.[24] These missions seemed ideal to bridge the gap between cislunar missions with durations of several months and Mars missions, which can take up to three years round trip. Further analysis expanded the flight time range from 270 to 720 days and demonstrated that SEP reduces IMLEO by a factor of two to three when compared to all chemical architectures, and can be as efficient as nuclear thermal rockets to increase the variety of accessible targets in a NEA exploration campaign.[25] These previous analyses examined NEA mission design from an architectural and technological perspective, while the present analysis seeks programmatic flexibility through a diverse set of mission opportunities. These individual missions provide the building blocks upon which a robust and worthy exploration program can emerge.

EXPLORATION ARCHITECTURE AND TECHNOLOGIES

Mission Profile

The four major flight elements are (1) an in-space transit habitat that provides sufficient room and equipment to keep the crew happy and productive while protecting them from deep-space radiation during, (2) a launch/entry capsule that is optimized to ferry the crew between Earth and the transit habitat in cisluanr space, (3) a SEP stage that transports the crew, habitat, and capsule from Earth to the NEO and back, and (4) a cryogenic propulsion system that injects the entire stack on an interplanetary transfer from Earth orbit. These elements may be launched separately and combined in Earth orbit over an extended time period to become a Deep Space Vehicle (DSV). The launch/entry capsule is based on the relatively mature Orion Multi-Purpose Crew Vehicle design comprising a 9 t capsule and 5 t service module (dry).[15, 26, 27] The Orion capsule is ideal to transport the crew to and from the DSV because it is designed for cislunar missions and provides 21 days of life support for four.[26] However, Orion is not ideal for missions longer than three months because its relatively cramped quarters (10 m^3, or about the room inside two minivans[15]) is right at the "performance limit" for a crew of only one.[28] Instead, a permanent in-space transit habitat can provide adequate room and necessary shelter from deep space (e.g. plenty of radiation protection) without compromising crew safety during launch and reentry (provided by Orion). We allocate 22 t for the NEO missions as a midpoint between ISS[29] and Mars surface[27] designs, while providing development margin for other flexible path missions.[30] In addition to the 22 t dry mass, the habitat also carries 20 kg/d of consumables for a crew of four.[27,31] The chemical propulsion system is assumed to be a cryogenic, zero boil-off LOX/LH2 system (450 s Isp) with 20% of the fuel mass as inert mass.[27, 32] The SEP stage is based on the NEA Design Reference Mission concept of Brophy et al.[22] Their design makes use of recent advances in large, light weight solar array technology[33–36] to provide 300 kW to the SEP thrusters. We limit the amount of time the crew spends in space by setting the SEP I_{sp} to a relatively low value of 1600 s, which increases the thrust (acceleration) at a fixed power level. A higher I_{sp} of 3000 s is used when the crew is not on board the DSV to reduce propellant mass at the expense of longer flight times. This range of Isp is ideal for Hall-effect thrusters,[37–39] which have an additional benefit of long lifetimes compared to other thruster types.[40] The margined mass of the SEP stage is calculated from a specific power of 30 kg/kW plus an additional inert mass of 15% of the propellant.

The DSV is assembled in LEO and spirals with SEP to an elliptical High Earth Orbit (HEO) with a C_3 of -2 km^2/s^2 (about a 10-day period). The individual element launches are not time critical because the spiral begins about two years before Earth departure.[25] The crew then is launched in the crew capsule for a rendezvous with the DSV in this orbit. The DSV with crew then performs an indirect escape maneuver at a 400 km perigee to reach the desired outbound hyperbolic asymptote for the interplanetary trajectory, which is then flown entirely with SEP. This staging and escape sequence is illustrated in Figure 1.

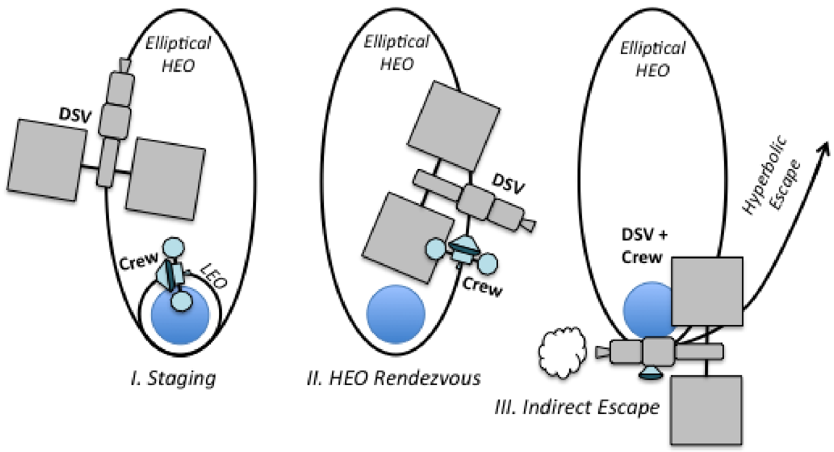

Figure 1. High Earth Orbit (HEO) Staging and Escape Sequence.

Because this architecture uses low-thrust propulsion, the pre-departure staging strategy provides a substantial performance benefit. Staging in the 10-day elliptical HEO with a departure burn at a 400 km perigee can reduce the chemical departure burn by 3.1 km/s for the DSV mass. A 2-year SEP LEO to HEO spiral provides this ΔV much more efficiently than a chemical burn. After the spiral, the DSV can be staged in orbits with perigee above the Van Allen belt and Lunar Gravity-Assists (LGAs) can be used to lower perigee to 400 km and orient the elliptical HEO prior to the departure burn. The crew capsule still uses chemical propulsion for the 3.1 km/s LEO to HEO ΔV, so the crew flight time is not affected by the duration of the SEP spiral and LGA trajectory. After departure, the crew pilots the DSV to the target asteroid with the SEP system. The minimum stay time at the asteroid is 30 days to provide ample exploration time with margin. Upon Earth return, the crew enters Earth's atmosphere directly from the inbound asymptote with an maximum entry speed of 12 km/s. (In comparison, lunar returns are around 11 km/s.) The transit habitat and SEP stage fly by Earth and capture into HEO a year later for refurbishment. By parking a reusable DSV in HEO, the IMLEO on subsequent missions is reduced by about 50 t. A summary of the parameters used to calculate mass and power is provided in Table 1.

Table 1. Mission Design Parameters

Parameter	Description	Value
Capsule dry mass	Crew module for launch and Earth entry, includes 21 d life support for crew of 4	14 t
Habitat dry mass	Reusable module to keep crew safe, happy, and productive in deep space	22 t
Crew consumables	Food, water, and air for a crew of 4	20 kg/day
Stay time at NEA	Provide ample time for exploration	30 d minimum
Departure orbit	Lunar crossing HEO with low perigee for efficient maneuvering	400 km alt. peri., 10 d per.
Maximum entry speed	Limits capsule entry requirements	12 km/s or 4.621 km/s V_∞
CPS I_{sp}	Cryogenic liquid H_2 and O_2	450 s
CPS inert/propellant	Expendable module with zero-boil-off	20 %
SEP spiral time	DSV from LEO to HEO without crew, based on Earth-Mars synodic period	2.14 yr
SEP spiral I_{sp}	High I_{sp} for mass-efficient LEO to HEO	3000 s, 63% jet/array
SEP interplanetary I_{sp}	Lower Isp increases thrust to limit in-space flight time for crew	1600 s, 50% jet/array
SEP inert/power	Reusable SEP stage including margin	30 kg/kW
SEP inert/propellant	Includes tanks and propellant margin	15%

Trajectory search and optimization

We set up a two-stage process to design low-thrust round-trip NEA missions. The first step is a broad search of computationally efficient impulsive trajectories, followed by computationally intensive optimization of low-thrust transfers filtered from the broad search. The entire catalog of known near-Earth asteroids (NEAs) in the JPL Small Body Database (http://ssd.jpl.nasa.gov/sbdb_query.cgi) comprising 7650 objects (as of January 29, 2011) was used in the near-Earth asteroid trajectory search. The trajectory search parameters included launch between 2019 and 2036, minimum 30-d asteroid stay time, maximum 720-d mission duration, and maximum 12-km/s total mission ΔV. A grid with seven-day intervals was applied to the launch, NEA arrival, NEA departure and Earth return dates and all combinations (within the flight time and ΔV limits) were examined. To save computational time the Earth-NEA legs where calculated independently of the NEA-Earth legs, then only combinations that satisfied the stay time and mission duration constraints were kept. The trajectory legs were computed using a robust and efficient (and highly recommended) Lambert solver algorithm from Gooding.[41] Once the mission ΔV was calculated the trajectories were sorted and filtered to provide the minimum ΔV for maximum flight times of 180, 270, 360, 540, and 720 days and for launch opportunities in 90-day increments. In this way the minimum ΔV trajectory in each quarter year for each of the maximum flight times was saved. The end result was ~50,000 filtered trajectories to ~1,400 unique targets.

The trajectories in the filtered set were used as the seed trajectories (initial guesses) in the low-thrust optimizer, MALTO.[42] The trajectories were optimized for maximum net mass assuming

240 t IMLEO and 300 kW maximum SEP power with the design parameters provided in Table 1. The net mass is the arrival mass at Earth minus the propulsion system inert mass. A second MALTO run with a maximum SEP power of 150 kW augmented this initial set to introduce lower power alternatives. The mass and power of the resulting trajectories are then scaled to provide the desired payload mass (transit habitat, capsule, and consumables) while maintaining the same C_3, ΔV, and flight time of the original trajectories.[43]

TRAJECTORIES TO NEAR-EARTH ASTEROIDS

NEA campaign considerations

The overall design objective is to determine the best target sets for different combinations of mass, power, and flight times, where the different capabilities represent flexible points in an evolving technology program and "best" targets are highly speculative based on the small amount of NEA data available. The NEA trajectories are grouped by maximum round trip flight time in Table 2–Table 5, where the 270-day trajectories provide options for the first asteroid missions following cislunar test flights and 720-day trajectories maximize exploration capability before the first Mars orbital missions. The IMLEO values are given for only the deep space vehicle (habitat, consumables, chemical departure stage, and interplanetary SEP) because the DSV is launched separate from the crew and drives the maximum launch vehicle capability. The crew rendezvous with the DSV in HEO a few days prior to departure via a separate launch that places 35 t (14 t capsule and 21 t LEO-HEO upper stage) into LEO. The power values (specified at 1 AU) also only pertain to the DSV because the interplanetary trajectory is independent of the LEO-HEO spiral trajectory. The nominal LEO-HEO SEP stage is sized to complete the spiral within 2.14 years, which requires a power/IMLEO ratio of 2 kW/t (at 3,000 s I_{sp}), and higher power ratios would reduce spiral time if desired. For example if the DSV IMLEO is 153 t (including spiral stage), then either a single 306 kW SEP system or two separate 153 kW stages could transport the DSV components from LEO to HEO in 2.14 years. Similarly, two 306 kW stages would transport the DSV to HEO in a little over 1 year. At a fixed power level, higher I_{sp} values decrease IMLEO but increase LEO-HEO spiral time. Once the crew and DSV rendezvous in HEO, they fly the same interplanetary trajectory regardless of how they reached the staging node. The C_3 and SEP ΔV columns indicate a relative breakdown of work performed by the cryogenic departure stage and the interplanetary SEP system. We note that the SEP ΔV will generally increase for I_{sp} values greater than 1600 s, even with the same initial acceleration (requiring higher power), because the mass ratio across the entire trajectory will change at a different rate. With this caveat, the C_3 and ΔV values are useful for broad system-level trade studies. The maximum Earth arrival V_∞ is 4.621 km/s, corresponding to an atmospheric entry speed of 12.0 km/s, though many trajectories return with a slower speed.

The spectral type and diameter of the targets give a rough portrait of their physical characteristics. Relatively little is known about the NEA population as a whole, so many targets are missing spectral and size information. In general B- and C-types are considered to be primitive carbonaceous objects and tend to have lower albedos (< 15%), while S-types are more stony and shiny (albedo > 15%), and X types are of uncertain physical nature, but have a known spectral curve. The diameter values for objects that have an unmeasured size and unknown albedo is estimated from the absolute magnitude (brightness) assuming a 15% albedo. Darker objects will tend to have higher actual diameters, while shinier ones will tend to have smaller diameters, and can easily range by a factor of two from the estimates in the tables. However, since other physical data tends to be unknown, we tend to favor larger objects to small ones when selecting example missions. While there is no reason to believe that the orbital distribution of small objects is any different than big ones, it is generally easier to find a viable trajectory to a small object due to the simple fact that there are so many more of them. Statistically speaking, an exploration program that can reach the top N% largest asteroids should also be able to include the top N% of any other figure of merit for asteroid target selection. In this case, size is used as a proxy for the degree of target variety and flexibility a given mission architecture provides.

Just as the physical characteristics of many asteroids are not well defined, the orbits of some asteroids are also uncertain. The last column in the tables provides the orbit condition code (as defined by the Minor Planet Center http://www.minorplanetcenter.org/iau/info/UValue.html) where low values (0–1) are considered to be well determined orbits (trajectory to the NEA likely exists as is), moderate values (2–3) are more uncertain (trajectory likely requires slight modifications), and large values (4 and above) represent objects that may not be easily recovered (general trajectory characteristics likely still exist, but at a different launch epoch). Therefore, not all of the trajectories in Table 2–Table 5 are guaranteed to exist after further orbital refinements.

Programmatic overview

For each of the maximum mission durations in Table 2–Table 5, around forty unique mission opportunities were picked "by hand" based on accessibility and speculative target value. The most accessible targets are marked in bold and generally have a combination of IMLEO < ~150 t and SEP power < ~150 kW, though the 720-day missions are purposefully biased toward more advanced technology assuming the exploration program provides more overall capability once astronauts can survive for up to two years in space. We also include targets that are more difficult to reach to examine how the accessible population varies as mission capability begins to approach the Mars exploration stage. For both "easy" and "difficult" targets sets, we seek mission sequences that provide a steady cadence of launch opportunities that not only sustains exploration but also accounts for uncertainty in the technology development schedule. Because technology development does not always keep up with shifts in space policy, a variety of mission options should remain on the table as the exploration program evolves.

For short duration missions (less than 270 days, with 30 days at the target) the accessible targets are largely limited to the large population of small and uncharacterized asteroids with poorly determined orbits. In Table 2 there are 15 opportunities (in bold) over the ~2020–2035 timeframe that are achievable with IMLEO and power levels commensurate with extended stays in lunar orbit. If larger SEP systems are available (up to 400 kW), then larger targets (at least 50 m) with lower orbit uncertainty (of 3 or less) are accessible at least six times during this timeframe. Only one well characterized asteroid, 2004 MN4 (Apophis) famous for its close approach to Earth in April 2029, provided reasonable IMLEO and power for short duration missions.

If one-year round trip missions are acceptable, then a more attractive set of accessible NEAs begins to emerge. In Table 3 there are 14 mission opportunities to targets that are estimated to be 100 m diameter or larger with a SEP system of at most 300 kW. If 300 kW systems are not developed, then a 200 kW SEP system can enable 19 missions (in bold) to moderately sized NEAs (larger than about 30 m) with at most 120 t launched to LEO for the DSV. A more modest technology development program would produce at least five missions achievable with 100 kW SEP systems and 100 t IMLEO.

These short-duration, low-power missions may be desirable to test the waters of deep space beyond the vicinity of the Earth and Moon, but eventually more difficult missions will be desired to begin testing systems for the exploration of Mars. A round trip mission to Phobos and Deimos is achievable for around 300 t IMLEO with 600–800 kW SEP systems and a round trip flight time of three years.[44] (Mars surface exploration is generally considered more difficult than a mission to its moons, though the natural gravity and radiation shielding of the planet provides some benefit.) The mission capabilities required for Mars exploration set a threshold on technology development during the NEA campaign (assuming "Mars is the ultimate destination for human exploration" [1]), which in turn informs the investment in technologies that provide the most leverage during the transition from cislunar excursions to sustainable deep space exploration. It is noteworthy that from this sustainable program perspective, the technologies and architectures that enable the quickest and cheapest NEA mission are not necessarily the most expedient for the overall program.

The development of a 200 kW SEP stage to propel a deep space habitat that can keep the astronauts safe, happy, and productive for up to 540 days enables the exploration of a diverse set of NEAs. In Table 4, there are 13 opportunities to visit an asteroid with a known spectral type and well-determined orbit for DSV IMLEO less than 130 t and SEP power up to 200 kW. With a 300 kW SEP stage there are 20 missions with 540 d flight time to targets that are estimated to be at least 500 m diameter. As exploration capability approaches levels required for Mars the variety of accessible NEAs continues to proliferate. A program that develops 250 t IMLEO capability (with separate launches), 400 kW SEP systems, and in-space mission durations of up to two years introduces regular access to kilometer-sized NEOs with nine examples in Table 5 and three others in Table 4. The exploration of a variety of targets that are relatively difficult to reach builds a proficiency in performing deep space missions that sets the stage for the human exploration of Mars.

The frequency of launch opportunities for a given mission increases not only with the ability to reach a range of targets but also when a NEA becomes accessible over multiple launch years. The ability to design a mission to a single target with multiple backup opportunities adds flexibility to the program schedule. While sets of mission opportunities emerge with impulsive-maneuver trajectories, they appear to be more common with low-thrust trajectories. The relatively high specific impulse of SEP reduces the sensitivity of IMLEO to the variations in ΔV across different opportunities, which makes it more likely for a given target to have similar mass and power requirements for separate launch years. For example, in Table 2 there is a pair of mission opportunities to both 2000 SG344 and 2004 MN4 in 2028 and 2029, and two separate opportunities to 2006 FH36. For 360 day missions in Table 3 there are three opportunities to 2007 UY1, and two pairs of launches to 2001 CQ36. With 540 day mission durations, 1989 UQ and 2002 OA22 have three opportunities over the timeframe of interest; there is a cluster of three potential missions to 1991 JW in 2026 and 2027; and there are two pairs of opportunities to 2001 CC21 in the early 2020s. Certain targets become accessible at regular intervals with longer flight times, where 1998 WT24, 2000 EX106, and 2003 UC20 appear three times, while 2002 RW25 and 2003 SD220 appear four times in Table 5. These last two targets have a semi-major axis less than Earth's (classified as an Aten orbit) and perihelia below Venus' orbit. While the frequency of opportunities to these targets is desirable from a programmatic perspective, the low perihelia increase thermal and, more notably, radiation doses that are less desirable from a mission design perspective. Thus the mission parameters provided in Table 2–Table 5 give an overview of which targets are accessible with a given technology, but they do not provide all of the information necessary to determine the suitability of a given mission.

Table 2. 180 and 270 Day Missions

Designation	Launch Date	DSV[a] IMLEO (t)	Power (kW)	C_3 (km^2/s^2)	SEP ΔV (km/s)	Spectral Type	Diameter (m)[b]	Orbit Code
2009 YF	6/18/2019	153	320	34.165	5.731		40	7
2008 EA9	11/19/2019 [c]	83	314	5.888	4.005		10	5
2001 GP2	**1/5/2020**	**61**	**90**	**6.898**	**2.033**		**14**	**6**
2007 UN12	**5/29/2020**	**71**	**170**	**2.856**	**3.525**		**6**	**4**
2007 UY1	10/16/2020	156	380	31.752	5.894		91	2
2006 FH36	11/9/2020	165	293	41.518	5.627		90	3
2011 AU4	3/31/2021	90	257	5.388	4.918		23	6
2010 UE51	5/9/2023	87	246	4.095	4.78		7	2
2010 UE51	8/11/2023 [c]	83	355	1.821	4.336		7	2
2001 QJ142	1/25/2024	100	323	3.988	5.668		71	6
2008 CM74	**9/30/2024**	**82**	**179**	**9.551**	**3.853**		**8**	**6**
2007 XB23	**12/10/2024 [c]**	**61**	**65**	**19.153**	**0.776**		**13**	**6**
2008 ST	**5/19/2025**	**79**	**184**	**7.157**	**3.789**		**13**	**5**
2008 JL24	9/22/2025	106	282	12.185	5.405		4	3
2009 HC	7/11/2026	99	253	16.305	4.242		38	4
2000 SG344	**5/26/2028**	**58**	**86**	**5.415**	**1.736**		**38**	**3**
2006 RH120	6/23/2028 [c]	73	279	1.605	3.644		4	1
2004 MN4	7/22/2028	141	257	32.724	5.527	Sq[45]	270[46]	0
2008 UA202	**1/20/2029**	**65**	**94**	**9.708**	**2.088**		**4**	**6**
2000 SG344	1/31/2029 [c]	72	224	6.238	3.223		38	3
2004 MN4	4/13/2029	129	208	34.407	4.594	Sq[45]	270[46]	0
2002 XY38	6/2/2029	177	397	32.427	7.067		89	1
2000 SG344	**11/23/2029**	**67**	**104**	**8.324**	**2.616**		**38**	**3**
2006 DQ14	8/25/2030 [c]	95	301	15.68	3.986		13	6
2009 YR	**9/6/2030**	**73**	**145**	**9.26**	**2.959**		**9**	**5**
2001 CQ36	2/3/2031	132	244	32.309	4.931		68[47]	2
2008 EA9	**10/1/2033**	**81**	**198**	**6.088**	**4.089**		**10**	**5**
2010 TE55	**6/11/2034**	**88**	**190**	**13.18**	**3.927**		**9**	**3**
2010 JK1	7/2/2034	131	323	25.459	5.292		46	6
2007 VU6	**10/14/2034**	**75**	**122**	**12.782**	**2.928**		**17**	**5**
2006 FH36	10/31/2034	151	363	27.066	6.312		90	3
2007 YF	**11/30/2034**	**83**	**158**	**14.214**	**3.446**		**38**	**5**
2010 JK1	2/2/2035	157	270	42.322	5.113		46	6
2007 VU6	**5/10/2035**	**84**	**130**	**17.935**	**3.169**		**17**	**5**
2006 BZ147	**10/25/2036**	**90**	**141**	**22.1**	**3.218**		**28**	**3**

[a]IMLEO given for deep space vehicle only. The separate crew launch adds 35 t.
[b]Diameter approximated from absolute visual magnitude assuming 15% albedo unless otherwise referenced
[c]180 day flight time

Table 3. 360 Day Missions

Designation	Launch Date	DSV[a] IMLEO (t)	Power (kW)	C_3 (km^2/s^2)	SEP ΔV (km/s)	Spectral Type	Diameter (m)[b]	Orbit Code
2008 RH1	9/20/2019	100	236	13.564	4.372		102	3
2002 BF25	7/20/2020	155	189	45.984	4.558		103	0
2001 CQ36	12/30/2020	118	272	16.938	5.427		68[47]	2
2007 UY1	**4/4/2021**	**106**	**144**	**24.428**	**4.090**		**91**	**2**
2001 CQ36	6/23/2021	94	254	2.729	5.315		68[47]	2
2006 SY5	9/7/2022	133	192	28.711	5.518		90[47]	3
2006 GB	9/26/2022	156	191	39.877	5.555		304	2
2008 EV5	12/30/2022	158	192	46.206	4.728	C[48]	450[49]	0
2007 SQ6	**10/3/2023**	**95**	**126**	**22.53**	**3.281**		**143**	**3**
2008 EV5	**6/23/2024**	**99**	**132**	**23.624**	**3.592**	**C**[48]	**450**[49]	**0**
1999 RA32	**9/14/2024**	**108**	**140**	**27.986**	**3.714**		**226**	**2**
2001 CC21	10/15/2024	206	410	33.020	8.163	L[50]	711	0
1999 RA32	3/13/2025	191	343	38.327	6.996		226	2
2010 WR7	12/10/2025	147	182	41.273	4.788		67	6
2009 HC	**4/18/2026**	**60**	**86**	**4.614**	**1.782**		**38**	**4**
1991 JW	6/3/2026	173	343	30.785	7.029	S[51]	500	0
2007 UP6	10/27/2026	162	197	45.836	5.029		91	2
1991 JW	5/9/2027	129	255	21.741	5.727	S[51]	500	0
2010 WR7	**7/23/2027**	**115**	**147**	**28.921**	**4.238**		**67**	**6**
2000 SG344	**4/9/2028**	**48**	**37**	**1.136**	**0.536**		**38**	**3**
2007 UP6	**4/21/2028**	**106**	**138**	**28.842**	**3.370**		**91**	**2**
2004 MN4	**4/24/2028**	**101**	**192**	**8.871**	**5.631**	**Sq**[45]	**270**[46]	**0**
2004 MN4	**4/13/2029**	**99**	**130**	**33.048**	**2.006**	**Sq**[45]	**270**[46]	**0**
2000 SG344	**10/22/2029**	**48**	**38**	**1.876**	**0.489**		**38**	**3**
2006 BJ55	**2/6/2030**	**102**	**134**	**26.760**	**3.345**		**49**	**6**
2001 CQ36	2/9/2030	187	223	53.676	5.296		68[47]	2
2001 CQ36	1/29/2031	105	201	23.066	3.727		68[47]	2
2006 BJ55	**8/14/2031**	**87**	**131**	**11.721**	**4.057**		**49**	**6**
2002 AW	3/18/2032	153	188	40.036	5.339		267	2
2007 UY1	8/23/2032	87	237	11.271	3.315		91	2
2009 TP	10/12/2032	149	182	47.718	3.897		67	6
2007 UY1	5/14/2033	178	301	37.073	6.664		91	2
2007 YF	**12/1/2033**	**118**	**150**	**33.282**	**3.748**		**38**	**5**
2006 BZ147	**2/28/2034**	**89**	**120**	**22.954**	**2.528**		**28**	**3**
2006 FH36	**3/27/2034**	**106**	**157**	**25.577**	**3.725**		**90**	**3**
2007 YF	**11/29/2034**	**87**	**163**	**13.481**	**3.494**		**38**	**5**
2006 BZ147	**2/6/2035**	**55**	**53**	**5.682**	**0.997**		**28**	**3**
2009 TP	**5/9/2035**	**85**	**89**	**21.561**	**2.588**		**67**	**6**
2005 GE60	6/10/2035	185	222	46.535	6.263		130	4
1998 XN17	11/27/2035	183	219	49.317	5.730		113	2
2002 CD	5/2/2036	156	345	15.382	8.184	C[52]	294	1
2001 TE2	9/25/2036	180	300	39.069	6.484		362	0

[a]IMLEO given for deep space vehicle only. The separate crew launch adds 35 t.
[b]Diameter approximated from absolute visual magnitude assuming 15% albedo unless otherwise referenced

Table 4. 540 Day Missions

Designation	Launch Date	DSV[a] IMLEO (t)	Power (kW)	C_3 (km^2/s^2)	SEP ΔV (km/s)	Spectral Type	Diameter (m)[b]	Orbit Code
2004 MN4	**10/13/2019**	**93**	**125**	**12.385**	**3.696**	**Sq[45]**	**270[46]**	**0**
2003 SD220	7/4/2020	192	232	33.706	7.687		1457	1
2001 CC21	12/4/2020	146	190	24.373	6.301	L[50]	711	0
2002 OA22	**3/27/2021**	**125**	**160**	**20.946**	**5.348**		**473**	**1**
1998 MW5	6/24/2021	165	278	18.399	7.994	Sq[50]	516	2
2006 SY5	**9/1/2021**	**91**	**109**	**13.112**	**3.451**		**90[47]**	**3**
2001 CC21	**12/18/2021**	**100**	**133**	**10.868**	**4.684**	**L[50]**	**711**	**0**
2006 GB	**3/30/2022**	**122**	**157**	**22.579**	**4.863**		**304**	**2**
2000 EE104	10/27/2022	163	200	32.720	6.180		318	0
2006 SY5	**3/4/2023**	**96**	**129**	**14.558**	**3.730**		**90[47]**	**3**
1998 MW5	6/27/2023	223	294	37.584	8.330	Sq[50]	516	2
2008 EV5	**12/28/2023**	**81**	**72**	**16.642**	**1.977**	**C[48]**	**450[49]**	**0**
1992 BF	1/21/2024	210	266	36.620	8.013	Xc[50]	510[47]	0
2004 FM17	3/22/2024	165	276	20.673	7.663		493	1
2001 CC21	**6/10/2024**	**129**	**164**	**18.324**	**6.060**	**L[50]**	**711**	**0**
1989 UQ	**8/22/2024**	**117**	**151**	**18.117**	**5.131**	**B[50]**	**730[47]**	**0**
2001 CC21	**5/30/2025**	**107**	**141**	**14.248**	**4.838**	**L[50]**	**711**	**0**
1999 AQ10	**8/23/2025**	**130**	**165**	**23.173**	**5.362**	**S[50]**	**295**	**0**
1991 JW	**5/16/2026**	**108**	**127**	**23.506**	**3.584**	**S[51]**	**500**	**0**
2001 TE2	9/21/2026	167	238	23.128	7.673		362	0
1991 JW	**11/20/2026**	**99**	**187**	**11.218**	**4.124**	**S[51]**	**500**	**0**
2004 MN4	**10/30/2027**	**86**	**117**	**8.764**	**3.517**	**Sq[45]**	**270[46]**	**0**
1991 JW	**11/19/2027**	**105**	**138**	**17.169**	**4.192**	**S[51]**	**500**	**0**
2001 TE2	3/18/2028	145	182	28.255	5.741		362	0
1992 BF	8/9/2028	149	295	16.309	7.046	Xc[50]	510[47]	0
2003 GS	10/16/2028	212	252	39.757	7.741		549	0
2004 FM17	3/21/2029	173	293	21.467	7.952		493	1
2006 SF6	**5/15/2029**	**135**	**171**	**26.435**	**5.297**		**360**	**2**
2002 OA22	**3/16/2030**	**132**	**167**	**22.658**	**5.627**		**473**	**1**
1989 UQ	**6/10/2030**	**126**	**160**	**23.338**	**5.034**	**B[50]**	**730[47]**	**0**
2001 QC34	12/29/2030	217	256	49.634	6.524	Q[53]	378	0
1989 UQ	**8/18/2031**	**118**	**152**	**18.716**	**5.081**	**B[50]**	**730[47]**	**0**
2001 QC34	1/12/2032	160	267	19.356	7.530	Q[53]	378	0
1999 JU3	6/28/2032	229	297	34.937	9.006	Cg[50]	980[54]	0
2002 OA22	**9/12/2032**	**119**	**154**	**19.570**	**5.085**		**473**	**1**
2002 CD	**10/3/2032**	**90**	**122**	**13.475**	**3.279**	**C[52]**	**294**	**1**
2000 HA24	10/18/2032	198	238	37.139	7.470		569	0
2002 CD	**10/5/2033**	**88**	**120**	**12.157**	**3.265**	**C[52]**	**294**	**1**
1996 FG3	2/22/2034	213	300	35.538	8.089	C[50]	1900[47]	0
1999 AQ10	**8/14/2034**	**131**	**166**	**22.783**	**5.522**	**S[50]**	**295**	**0**
1996 FG3	2/5/2035	184	343	21.215	8.305	C[50]	1900[47]	0
1999 RQ36	9/14/2035	141	176	29.843	5.170	B[55]	580[56]	0

[a]IMLEO given for deep space vehicle only. The separate crew launch adds 35 t.
[b]Diameter approximated from absolute visual magnitude assuming 15% albedo unless otherwise referenced

Table 5. 720 Day Missions

Designation	Launch Date	DSV[a] IMLEO (t)	Power (kW)	C_3 (km^2/s^2)	SEP ΔV (km/s)	Spectral Type	Diameter (m)[b]	Orbit Code
1999 JU3	6/16/2019	183	246	13.635	9.253	Cg[50]	980[54]	0
2003 UC20	**11/17/2019**	**149**	**151**	**22.175**	**6.287**	**C[52]**	**813**	**0**
2003 CY18	7/31/2020	210	278	46.093	5.701		861	0
1982 HR	10/4/2020	205	463	18.151	8.499		300[57]	0
1996 GT	11/4/2020	145	364	19.039	5.085	Xk[50]	880	0
1989 FB	4/6/2021	246	392	32.251	8.895		1300[57]	0
2000 HA24	**8/7/2021**	**148**	**185**	**17.150**	**6.741**		**569**	**0**
2003 SD220	**12/16/2021**	**161**	**174**	**28.997**	**5.999**		**1457**	**1**
1996 FG3	**1/12/2022**	**159**	**198**	**17.153**	**7.467**	**C[50]**	**1900[47]**	**0**
2002 NW16	7/10/2022	233	499	25.449	8.660		887	0
1996 GT	10/15/2022	172	244	34.822	5.356	Xk[50]	880	0
1996 FG3	**4/10/2023**	**165**	**204**	**16.818**	**7.866**	**C[50]**	**1900[47]**	**0**
1982 HR	10/6/2024	205	453	18.471	8.536		300[57]	0
2003 SD220	**12/22/2024**	**176**	**179**	**27.573**	**7.131**		**1457**	**1**
1999 FP59	9/10/2026	175	427	30.830	5.012		835	0
2002 RW25	**9/11/2026**	**136**	**131**	**18.472**	**6.021**		**606**	**1**
2004 OB	11/8/2026	171	422	18.734	6.645	C[52]	601	1
2003 SD220	7/4/2027	250	368	23.216	10.494		1457	1
2000 EX106	1/24/2028	232	448	24.951	8.998	S[50]	621[47]	0
2007 HF44	**12/13/2028**	**134**	**169**	**28.979**	**3.934**		**498**	**3**
2000 EX106	2/10/2029	181	222	22.091	8.026	S[50]	621[47]	0
2002 RW25	**9/12/2029**	**136**	**147**	**17.432**	**6.062**		**606**	**1**
1998 WT24	12/8/2029	210	237	43.140	6.403	E[58]	420[58]	0
1991 VH	2/21/2030	243	289	27.703	10.014	Sk[59]	1120[47]	0
2002 TD60	6/2/2030	159	397	9.922	7.318		501	0
2003 UC20	**12/2/2030**	**141**	**120**	**21.641**	**6.023**	**C[52]**	**813**	**0**
2007 HF44	**12/10/2030**	**133**	**168**	**28.674**	**3.886**		**498**	**3**
2002 TD60	6/1/2031	191	298	21.386	8.233		501	0
1998 YN1	5/5/2032	205	427	28.650	7.144		862	0
2000 HA24	**7/30/2032**	**149**	**187**	**16.396**	**6.939**		**569**	**0**
2002 RW25	**9/13/2032**	**136**	**162**	**15.908**	**6.155**		**606**	**1**
1992 SL	9/14/2032	203	487	33.354	5.957		903	0
2003 UC20	**12/3/2032**	**144**	**144**	**19.694**	**6.320**	**C[52]**	**813**	**0**
1998 WT24	12/12/2032	205	246	32.594	7.690	E[58]	420[58]	0
2003 SD220	7/7/2033	251	337	27.542	10.106		1457	1
1999 VG22	2/24/2034	184	315	34.623	5.727		662	1
2002 RW25	**9/13/2035**	**136**	**159**	**15.774**	**6.216**		**606**	**1**
1998 WT24	12/14/2035	209	252	27.064	8.694	E[58]	420[58]	0
1999 VG22	1/29/2036	146	277	23.158	5.098		662	1
2000 EX106	2/12/2036	173	213	20.514	7.825	S[50]	621[47]	0
2001 QC34	**7/6/2036**	**144**	**182**	**11.508**	**7.373**	**Q[53]**	**378**	**0**
1994 CN2	9/6/2036	144	363	16.482	5.416		1668	1

[a]IMLEO given for deep space vehicle only. The separate crew launch adds 35 t.
[b]Diameter approximated from absolute visual magnitude assuming 15% albedo unless otherwise referenced

Individual mission examples

The list of targets generated from an accessibility study provides an overview of which target characteristics can be associated with a given set of technologies. A NEA exploration campaign emerges from this overview by choosing a sequence of missions that can accomplish the objectives for human spaceflight. Flexibility is introduced to the exploration program by designing multiple target sequences that account for delays in technology development, changes to the mission schedule, and shifts in overall program objectives and policy. However, the current design of mission sequences is necessarily incomplete given the dearth of information available for most targets.[17] Nevertheless, we provide example mission sets with different technology options assuming that the first asteroid mission occurs in the 2020s and that the overall objective of the NEA campaign is to develop a proficiency in deep space that leads to the human exploration of Mars. A diverse catalogue of mission sequences provides the flexibility necessary to adapt to an evolving development path to Mars.

We believe that the most exciting and productive NEA missions push technology to a midpoint between current designs and Mars capability and explore asteroids that are at least a few hundred meters across. Four such examples are provided in Figure 2, where an IMLEO of 150 t (including crew launch) and flight time of 540 days are half the Mars-orbital requirements and 150 kW is a fifth of the Mars design.[44] The variety of launch years to these targets provides the flexibility to complete an important step towards Mars as soon as the technology can be developed.

While these advanced missions are attractive for their exploration value, we do not suggest that the first long-duration test flights occur on a NEA mission. Instead, the assembly of the DSV in high-Earth orbit and exploration of the Moon from lunar orbit provide productive and meaningful missions that can qualify vehicles for deep space while the astronauts remain only a few days from Earth. Even if the first asteroid mission is designed to last only a few months, cislunar test flights provide more robust abort options than deep space NEA excursions. The key technological barrier does not appear to be launching mass to orbit or high-power SEP systems, but instead the mitigation of radiation hazards. Many propose NEA excursions with limited mission duration,[8–16] which limits the cumulative radiation dose. (Alternatively, additional radiation shielding provides a prophylactic against radiation exposure during longer missions.) While the environmental effects on humans in deep space remains a key issue, there are many options for NEA exploration with mission durations of a year or less. If a 300 kW SEP system is developed then 2006 FH36 and 2004 MN4 provide 270-day missions to sizable targets in 2020 and 2029, respectively. These missions are portrayed in Figure 3, where the same SEP system and launch vehicles combined with an upgraded habitat provide one-year mission to 1991 JW in 2027. If a 300 kW SEP system is not developed, several options for one-year durations still exist at lower power levels where a mission to 1999 RA32 in 2024 is given as an example.

Alternatively, if more resources are allocated to developing deep space habitation as opposed to launch vehicle capacity and SEP systems with ISS-sized arrays, then a different set of missions emerge. In Figure 4 a 100 t DSV with a 130-kW SEP stage provides an opportunity to explore 2008 EV4 in 2024. Alternatively, a mission with much smaller IMLEO and power is available to the much smaller target 2000 SG344 in 2028 (and again in 2029) following a more languid technology development schedule. Further development of two-year habitats enables a steady launch cadence to relatively large objects with 150-kW systems as exemplified by the 2002 RW25 and 2003 UC20 missions in 2029 and 2030.

Provided a set of missions with a variety of targets and technologies, a NEO exploration program can be designed to progress from cislunar capability up to the threshold of Mars exploration. A notional sequence in Figure 5 begins with a six-month, low mass, low power mission to 2007 XB23 in 2024. We note that this mission is exceptional, but serves as a proof of concept for the mission architecture using limited exploration capability. As new NEAs are detected, it is assumed that missions with similar trajectories will be available in multiple launch years with better characterized and potentially larger targets. Alternatively, the capability to survive up to a year in deep space could be developed during cislunar and lunar missions, which dramatically increases the variety of known accessible targets. A 330-day mission with moderate mass and power requirements to Apophis (2004 MN4) could then occur in 2029. Following this mission, any of the NEAs in Figure 2 would make a respectable next target, or the development of higher power and launch capability enables a 500-day mission to 1996 FG3 in 2034. This NEA makes an attractive target because it is large, potentially primitive, and has a satellite. The addition of a binary adds significant complexity to the mission, which would have to be considered in context of eventual Mars (including Phobos and Deimos) exploration objectives. The final mission in Figure 5 is to the relatively large Mars-crossing asteroid 1994 CN2. This trajectory is unique in that it remains outside of Earth's orbit for the duration of the mission, and may provide the closest analogue to a Mars orbital mission.

The opportunities depicted in Figure 2–Figure 5 provide a small subset of the example mission sequences that can be created from the target lists in Table 2–Table 5. Further, these target lists represent a hand-picked portion of the steadily growing catalogue of NEAs that are accessible with different technology options. Depending on how technology development for deep space evolves, there are myriad combinations of missions that create a flexible campaign to explore NEAs. While the population of currently known asteroids that provide short duration missions is relatively anemic, there is a variety of enticing missions for flight times of one to two years. As human spaceflight transitions to deep space exploration, NEAs provide many options to push farther from Earth and closer to Mars.

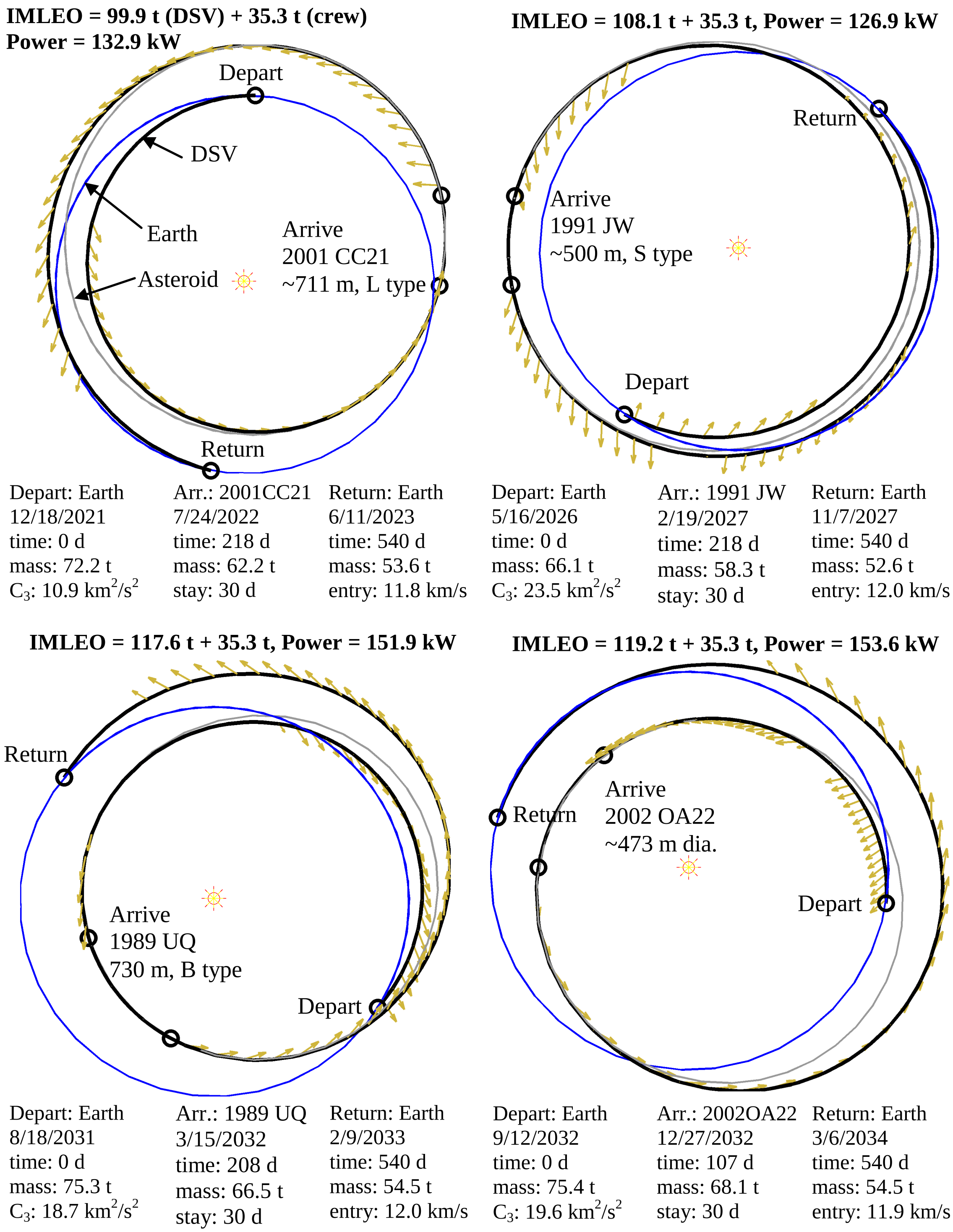

Figure 2 Multiple NEAs 500 m or larger become accessible with 150 t IMLEO, 150 kW SEP power, and 540 day flight time.

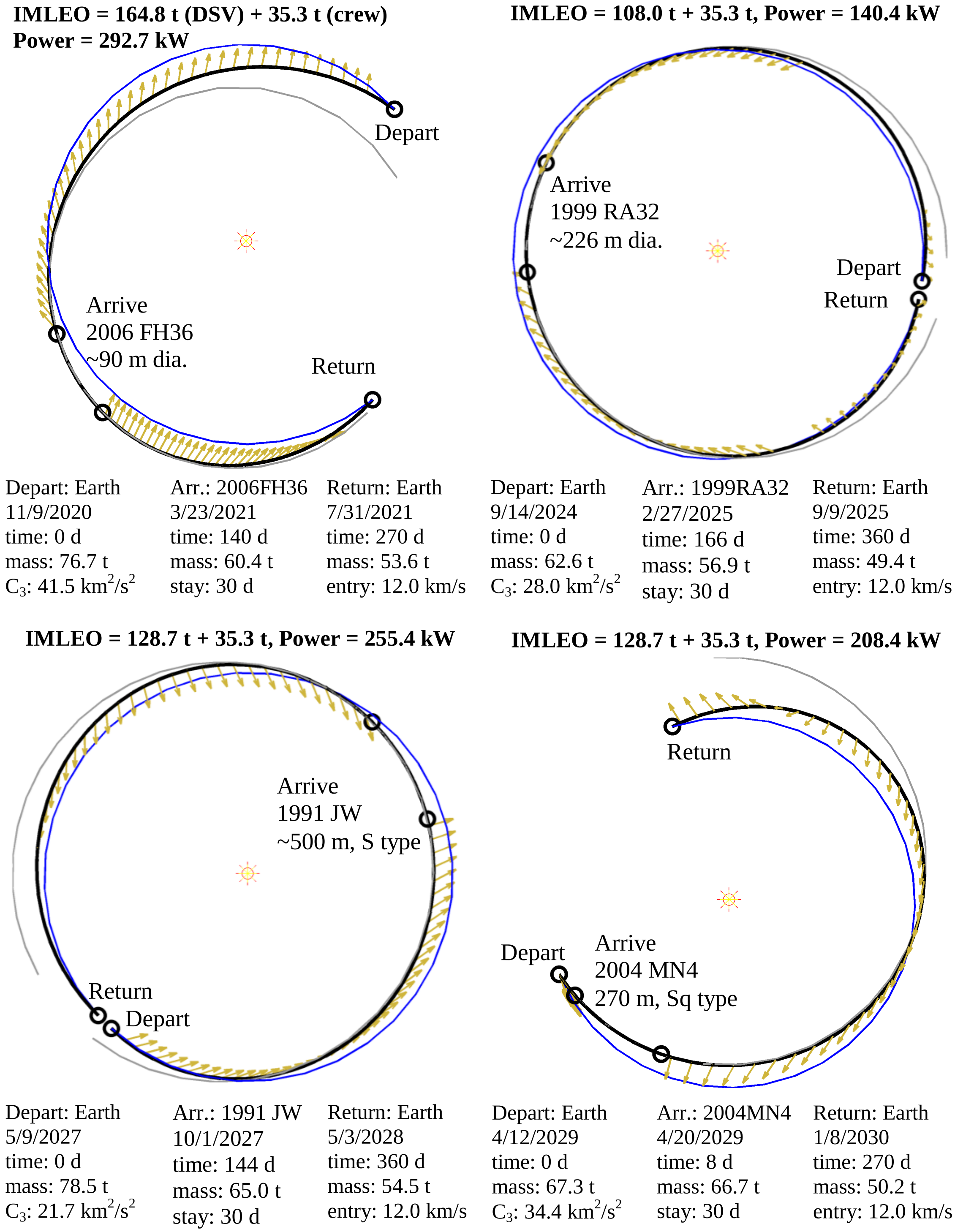

Figure 3 Mission durations of one year or less occur regularly with 300 kW SEP systems.

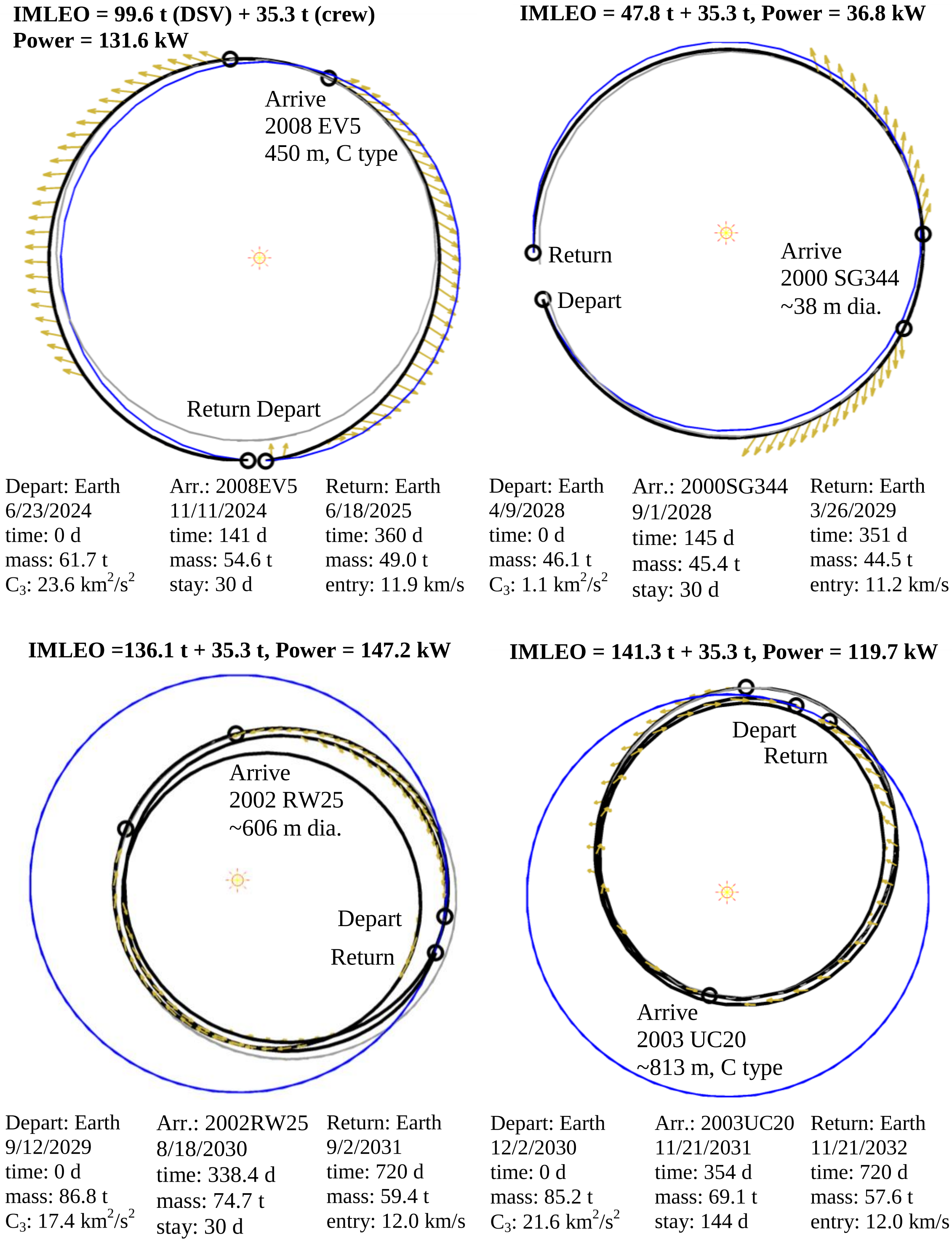

Figure 4 A variety of NEA characteristics and mission durations exist for SEP power below 150 kW.

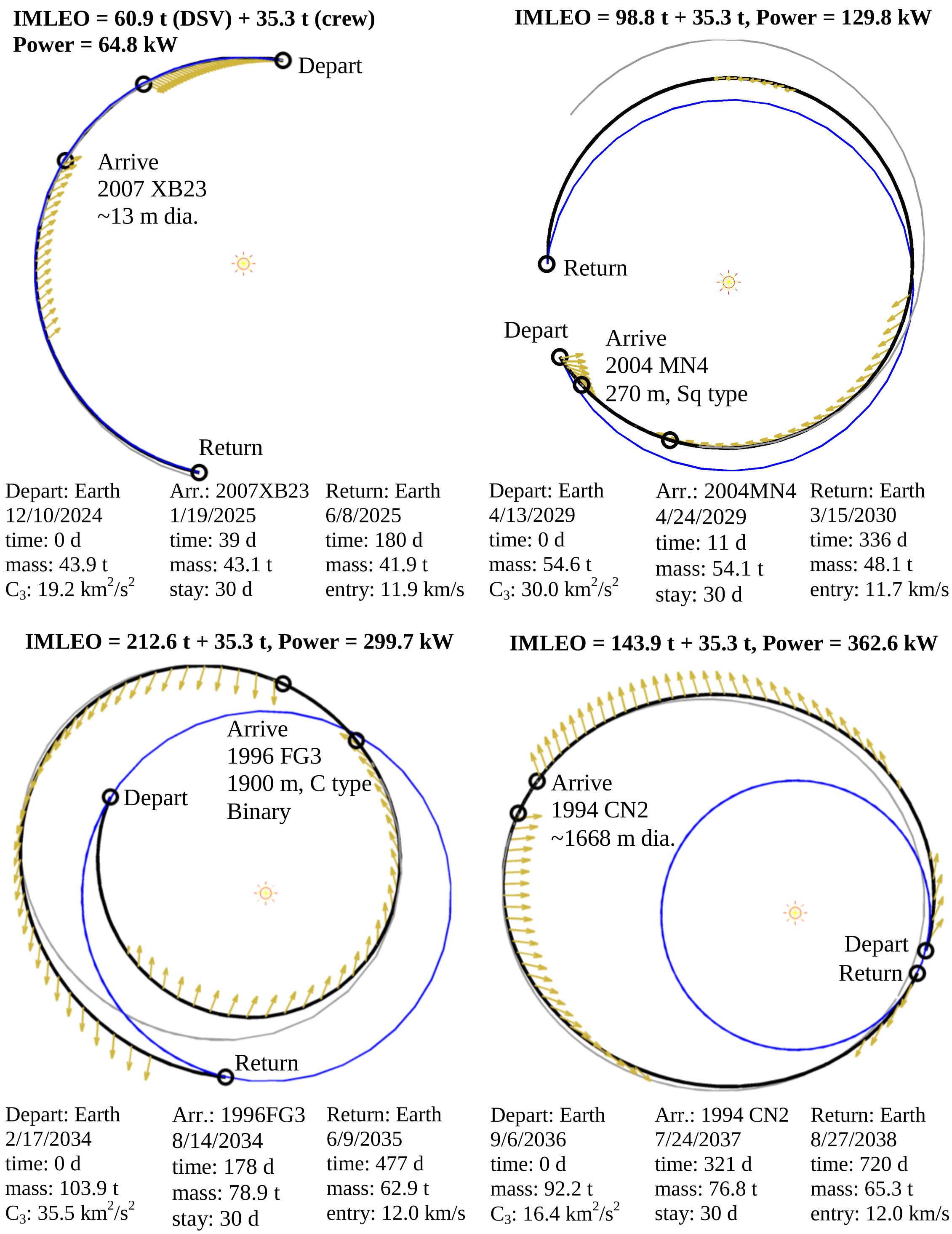

Figure 5 Mission targets become increasingly more attractive as exploration capability matures.

CONCLUSIONS

The hybrid combination of a high thrust Earth departure stage with a high power SEP stage for interplanetary flight produces a much larger set of NEA missions than with chemical propulsion alone. A progressively wider selection of larger asteroids become accessible as the SEP power level or mission flight time increases, suggesting a NEA exploration campaign that incrementally develops technologies to a level needed for the eventual exploration of Mars. The individual missions of this campaign could be combined into multiple sequences that connect a path from cislunar space to Mars orbital missions, where each step adjusts to evolving technological capabilities and variable program objectives. The design of such a NEA campaign calls for a range of launch opportunities from those requiring limited technology, to initiate deep space exploration, and those with advanced technology to establish the capability needed to explore objects as distant as Mars. The target characteristics associated with each phase in the mission sequence are strongly correlated to the mission duration. Missions with 180-day flight time and relatively low mass and power requirements are rare, but do exist sporadically over multiple years.

Both the hybrid SEP architecture and impulsive ΔV architectures have limited target sets for missions of 270 days or shorter. Accessible targets with shorter flight times are mostly limited to objects that are less than 100 m in diameter and have poorly resolved orbits, simply because they are the majority of known NEAs. For one-year missions, a much larger fraction of the NEA population becomes accessible, and multiple launch opportunities to objects larger than 100 m with suitably defined orbits become possible. At a 540-day mission duration the accessible population expands dramatically, generating multiple opportunities to 500 m objects with a diversity of taxonomic types. The list of currently known NEAs includes many kilometer-sized targets accessible with two-year flight times and 400 kW SEP systems, a capability which brings NEA exploration to the threshold of Mars exploration. An entire spectrum of asteroid missions exists between the most accessible targets and the most challenging destinations, providing multiple options to establish a flexible and evolvable human exploration program.

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