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Phobos and Mars orbit as a base for asteroid exploration and mining

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A R T I C L E I N F O

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A B S T R A C T

The number and total mass of high value near-Earth asteroids (NEOs) are limited. If space exploration and mining becomes profitable then at some point it will benefit from moving on to the far greater resources of the Main Belt Asteroids (MBAs). Most MBAs are energetically too hard to reach with present technology from low Earth orbit. An alternative is to use Mars orbit as a base from which to conduct MBA research, prospecting, and mining. We have developed PARC: Python Asteroid Rendezvous Code which uses a fast Lambert's problem solver and straightforward maneuver schemes to survey the delta-v necessary to rendezvous with any known asteroid from either Earth or Mars orbit given a specified launch date and time of flight. We used PARC to investigate whether Phobos-like orbits around Mars at altitudes of ~9000 km, are more energetically favorable and useful locations from which to dispatch missions to MBAs. We find that they are. From a Phobos-like orbit, around 100,000 known MBAs have delta-v <4 km s^{-1} and some 340,000 have delta-v <5 km s^{-1}, nearly a thousand times that of NEOs. Unsurprisingly, the most accessible MBAs have low inclinations ($i < 5$ deg) and small semi-major axes ($2.0 < a < 2.5$ AU). Known MBAs are much larger than NEOs, so the total mass that is accessible is larger by ~10,000 times the accessible mass in NEOs. As a result, a growing economy that utilizes space resources or large scale exploration missions will likely find Mars orbit convenient. The stable platform and modest gravity afforded by Phobos would make it a natural first choice. Once Mars orbit has a profitable economy, with high value trans-shipments, the Martian surface may also become an economically valuable outpost. This value may then stimulate settlement.

1. Introduction: where the resources are

Assuming asteroid resources become profitable to mine (i.e. ore-bearing), then long-term use of these resources requires access to the Main Belt. That is because the number and total mass of high value near-Earth objects (NEOs) are limited (Elvis, 2014). The NEOs contain ~10^{14} metric tonnes of material (see Section 3.2), but the asteroid Main Belt - between the orbits of Mars and Jupiter - is where the great majority of the accessible resources of the Solar System reside. The Main Belt contains ~10^{18} metric tonnes of material mass, ~10,000 × the mass found in NEOs. Even if most of the Main Belt material were set aside as wilderness parks, assuming that asteroids share a common ~30% iron mass composition with Earth (including the core), that is still more than a million times the known surface iron resources on Earth (Elvis and Milligan, 2019). Moreover, as space missions become longer in duration and venture away from Earth orbit, it may become far more viable to acquire bulk resources in the Main Belt, rather than exporting materials out of Earth's gravity well. Such resources could include structural materials such as iron, propellant precursors or “volatiles” (Sonter, 1997), water, or in rare cases: precious metals (Hein et al., 2020).

Large scale mining will require large processing plants to concentrate (or “beneficiate” in mining industry terms) the ore rapidly enough to give a good return on investment. These plants need to be easily accessible from the mining site, as the raw ore will be far more massive than the final refined product, and moving mass in space is hard, thanks to the inexorable Rocket Equation (Forward, 1995). The processing plants are themselves likely to be quite massive and not readily moved from asteroid to asteroid. There are then two options: (1) mine a large asteroid so the beneficiation plant can remain in situ for a long time, or (2) mine multiple asteroids that have low asteroid-to-plant delta-v values, as this is the leg of the journey on which the largest mass is being moved. The largest asteroids may well be subject to mining restrictions (Elvis and Milligan, 2019), so option (1) may not be allowed. From Earth, reaching the MBAs is daunting. With a minimum delta-v ~7 km s^{-1} to rendezvous from low Earth orbit (LEO) with the easiest to reach MBA, compared with ~4 km s^{-1} needed for the easiest to reach near-Earth asteroids (NEOs) from low Earth orbit (Taylor et al., 2018). Small changes in delta-v make for big differences in deliverable payload, thanks again to the rocket

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equation (see e.g. Elvis et al., 2011).

In the second case, Phobos may be a convenient beneficiation site choice for a number of reasons:

- As Phobos would not be a mining site, restrictions on its use are less likely than on Ceres or the other large asteroids.
- The relatively modest delta-v from Phobos to Mars escape velocity (C3 = 0) of ~1 km s^{-1} means that bringing large masses of raw, or semi-raw, asteroid material to Phobos is plausible.
- Exerting large forces on asteroid material will be easier on Phobos than in an asteroid's native orbit, as this moon provides a massive inertial platform (10^7 Mt) against which to push (Cox, 2000).
- The large mass of rock on Phobos itself can be used to provide radiation shielding for any humans involved, for instance in maintenance and repair of the beneficiation plant, especially before significant material is imported for additional shielding.
- The surface of Mars is relatively readily accessible from Phobos' orbit (delta-v ~4.64 km s^{-1}) (Elvis et al., 2011). In the longer term, once major and profitable mining activity is taking place in Mars orbit with high value trans-shipments occurring there, the planet's surface may become economically valuable. A Phobos base for Main Belt mining might then encourage large scale exploration and use of the Martian surface, which in turn may encourage settlement.

Given these considerations we decided to test if a mining base in Mars orbit, specifically a Phobos Mars orbit (PMO) offered significant advantages when compared with a base in LEO. While previous studies have analyzed the accessibility of the NEOs from Earth (e.g., Taylor et al., 2018, Elvis et al., 2011)) and more recently from Mars (Biktimirov et al., 2019), the Main Belt, which contains over 93% of known asteroids and over 95% of the known mass in asteroids, is almost entirely neglected. As such, in this work we examine the accessibility of both MBAs and NEOs in terms of the delta-v—the primary limiting factor in accessibility—necessary for successful rendezvous.

2. Delta-V calculation methods

2.1. Orbital mechanics

Expanding on the previous work of Taylor et al. (2018) (hereafter referred to as T18), we adopt the same the Patched Conics approximation (Hohmann, 1960) for orbital mechanics, in which a body in orbit is affected by a single dominant gravity well. We use a purely Keplerian approach to orbital mechanics in which 3-body interactions and relativistic effects are ignored. Such effects are negligible for orbits near Mars and the Asteroid Main Belt, and are unnecessary for an initial delta-v survey identifying potential exploration and mining targets. All orbital maneuvers used in this study assume high thrust, brief operation, propulsion systems (e.g. LOX/LH2 engines) such that the velocity change at each maneuver is effectively instantaneous. While low-thrust schemes such as ion engines could also be used for asteroid rendezvous (Coverstone-Carroll et al., 1999), these schemes are not considered for this study.

In an asteroid rendezvous a spacecraft matches the asteroid's orbit exactly so that there is zero relative velocity between the asteroid and spacecraft. The delta-v necessary for an orbital insertion and operations around even *Ceres* is negligible due to its low gravity ($g_{Ceres} = 0.03g$) (NASA, 2016).

In T18 all orbital maneuvers started in a 100 km-altitude circular LEO, and were developed to computationally simple estimates of delta-v in the spirit of the Shoemaker-Helin equations (Shoemaker and Helin, 1978). Due to the Earth's low orbital eccentricity the Earth's heliocentric orbit was approximated as a perfect circle. The resulting azimuthal invariance of the starting conditions simplified the calculations. This approximation does not apply to the case of Mars due to its significant eccentricity of e = 0.0934 (Cox, 2000). In addition, the use of the inclination of the asteroid orbit to the ecliptic is no longer appropriate for Mars, as Mars' orbit is inclined 1.850° to the ecliptic (Cox, 2000). Given these challenges, we have advanced our approach to delta-v calculation beyond the Shoemaker-Helin inspired approximations to consider real timing based maneuvers in a more general vector-based framework.

Table 1
These definitions are adopted from the Minor Planet Center. In this table, q is periapsis (AU), a is semimajor axis (AU), e is orbital eccentricity, and i is orbital inclination in degrees.

Orbit Type	Orbit Criteria	Objects
Near-Earth Objects (NEOs)	$q < 1.3$	27,505
Mars Crossers (MCs)	$1.3 < q < 1.665$	18,797
Hungaria	$1.8 < a < 2$, $i > 12$, $e < 0.25$	28,085
Phocaea	$2.2 < a < 2.5$, $i > 12$, $e < 0.25$	12,253
Hilda	$3.7 < a \leq 4.1$, $i \leq 20$, $e \leq 0.3$	5176
Jupiter Trojan	$4.8 \leq a < 5.4$, $e \leq 0.3$	11,363
Distant Object	$a > 6$ and is none of the above	4677
Main Belt Asteroids (MBAs)	$2.15 < a < 3.28$ or is none of the above	1,045,019
All		1,152,875

2.2. Timing based approaches

While the updated maneuvers from T18 provide good estimates of rendezvous delta-v, they assume specific alignments of Earth/Mars with target asteroids that may not produce the lowest possible delta-v or even occur in any reasonable time span. We thus update our approach in the spirit of Biktimirov et al. (2019). In their work, Biktimirov et al. selected 88 NEOs that satisfied an estimated delta-v threshold of 6.3 km s^{-1}, as well as spectral type and size requirements. For each of these NEOs, they solved Lambert's problem for Mars based launches from 2050 to 2070 allowing 100–800 days of transit time for rendezvous with the target NEA. We now expand this approach to include all 1,152,875 known asteroids (as of December 2021).

We adopted and implemented the algorithm presented in Izzo (2015) to efficiently solve Lambert's problem to find trajectories that result in a rendezvous with an asteroid from a starting planet given both a departure date and a fixed time of flight. We then used this tool to generalize the T18 maneuvers to allow for flexible departure dates and flight times while using real ephemerides for both the starting planet and target asteroid.

The first and simplest maneuver scheme is a two burn method. In this trajectory, a spacecraft executes one burn while in a parking orbit around the starting planet (Earth or Mars) that both escapes the planet's gravity and establishes the Lambert problem trajectory that will result in positional rendezvous with a target asteroid. The spacecraft then performs a second burn at the point of rendezvous to match the asteroid's orbit.

The “Two Burn Method” of T18 is a special case of this maneuver scheme in which the target asteroid is at its ascending or descending node at the time of rendezvous, and the starting planet is 180° away form this node at launch. This maneuver method has one major caveat: when the planet at the time of departure and the asteroid at the time of rendezvous are near 180° apart in celestial longitude, the plane containing both of these points and the Sun will often have a very high inclination relative to the orbital planes of the starting planet and asteroid. As the Lambert trajectory is constrained to lie within this plane, orbital alignments most similar to the Hohmann alignment often return higher delta-v than expected for what should be a favorable alignment.

To address this problem, we introduced a three burn method. In this scheme, we perform the first burn to escape the starting planet's gravity and establish a transfer orbit in the plane of the starting planet's solar orbit. This transfer orbit is determined by the single revolution Lambert solution for a transfer to the target asteroid as if its position at the time of rendezvous were rotated into the plane of the starting planet's orbit. When the spacecraft is halfway (in celestial longitude) to the modified rendezvous point, we re-solve the Lambert Problem using the spacecraft's

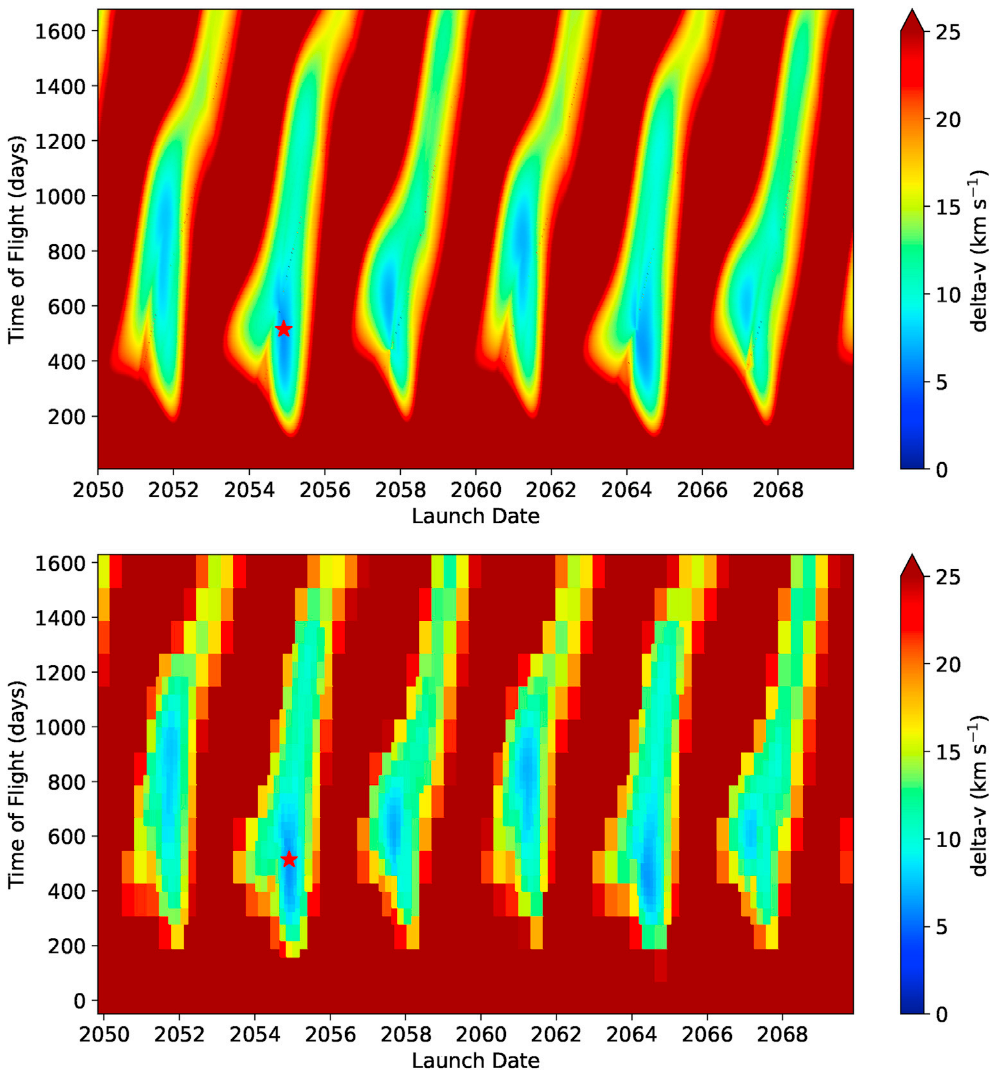

Fig. 1. Top: Delta-v map for Mars to Ceres rendezvous evaluated at 5 day precision from 2050 to 2070. The red star marks the departure day and time of flight that minimizes delta-v. Bottom: Same as above, but using the progressive gridding scheme and solving to one day precision. Note that regions of lower delta-v are resolved at higher resolution than uninteresting regions of higher delta-v. This progressive gridding scheme is a factor of ~5000 faster than evaluating the entire grid at 1 day precision.

current position, the actual (out of plane) rendezvous position of the asteroid, and the remaining time of flight to calculate and execute a broken plane maneuver. This second burn rotates the transfer orbit out of plane for the actual rendezvous. When the spacecraft reaches the rendezvous point, it executes a third and final burn to match orbits with the target asteroid.

The “Three Burn Method” of T18 is again a special case of this maneuver scheme in which the celestial longitude of the planet at launch matches the asteroid's periapsis longitude. The updated three burn method successfully fixes the two burn method's out of plane problems at conjunction by forcing the initial transfer orbit to be in plane, and correcting for and relative inclination with the broken plane maneuver. The timing of the broken plane maneuver is a free parameter in this scheme, which we have set to be halfway in celestial longitude between launch and rendezvous. Further tuning of this parameter could potentially result in lower delta-v trajectories, but we leave this for a future study due to computational constraints.

We adopt the MPC definitions of asteroid orbit types[1] in this study (summarized in Table 1). Phobos, the larger and lower orbit moon of Mars, is a likely site for future Martian orbital infrastructure, so our starting parking orbit around Mars is set to a circular orbit with Phobos' semi-major axis of 9376 km (5986 km above the Mars surface, on average) which we hereafter refer to as “Phobos Mars Orbit” (PMO). For simplicity, this orbit is assumed to be in the plane of the initial transfer orbit. In reality, Phobos' orbit is inclined relative to the ecliptic, instead aligning closely with Mars's equatorial inclination of 25.19°. We neglect this offset in our calculations, as the increase or decrease in delta-v caused by the inclination would be highly dependent upon both the intended transfer orbit and the orbital alignment of Phobos, Mars, and the target asteroid. Taking this into account would require precise ephemerides for Phobos, which are beyond the scope of this work. We estimate that the maximum change in calculated delta-v for an average main belt asteroid from this effect is ~0.3 km s^{-1}, but most cases will be less affected. Our starting orbit from Earth (LEO) is a circular orbit at 400 km above the Earth's surface—the orbital height of the ISS—and again has an inclination matching the transfer orbit's ecliptic inclination.

2.3. PARC: Python Asteroid Rendezvous Code

We implemented the above maneuver schemes in Python, and created a package: PARC: Python Asteroid Rendezvous Code. PARC implements both orbital rendezvous methods as well as the underlying Lambert solver in Python 3.7. We designed PARC to be both transparent and accessible, therefore the only prerequisites are a base Python 3.7+ environment, and the numpy package. For large scale applications, PARC's functions scale almost linearly when called in batches by the

[1] https://minorplanetcenter.net/Extended_Files/Extended_MPCORB_Data_Format_Manual.pdf.

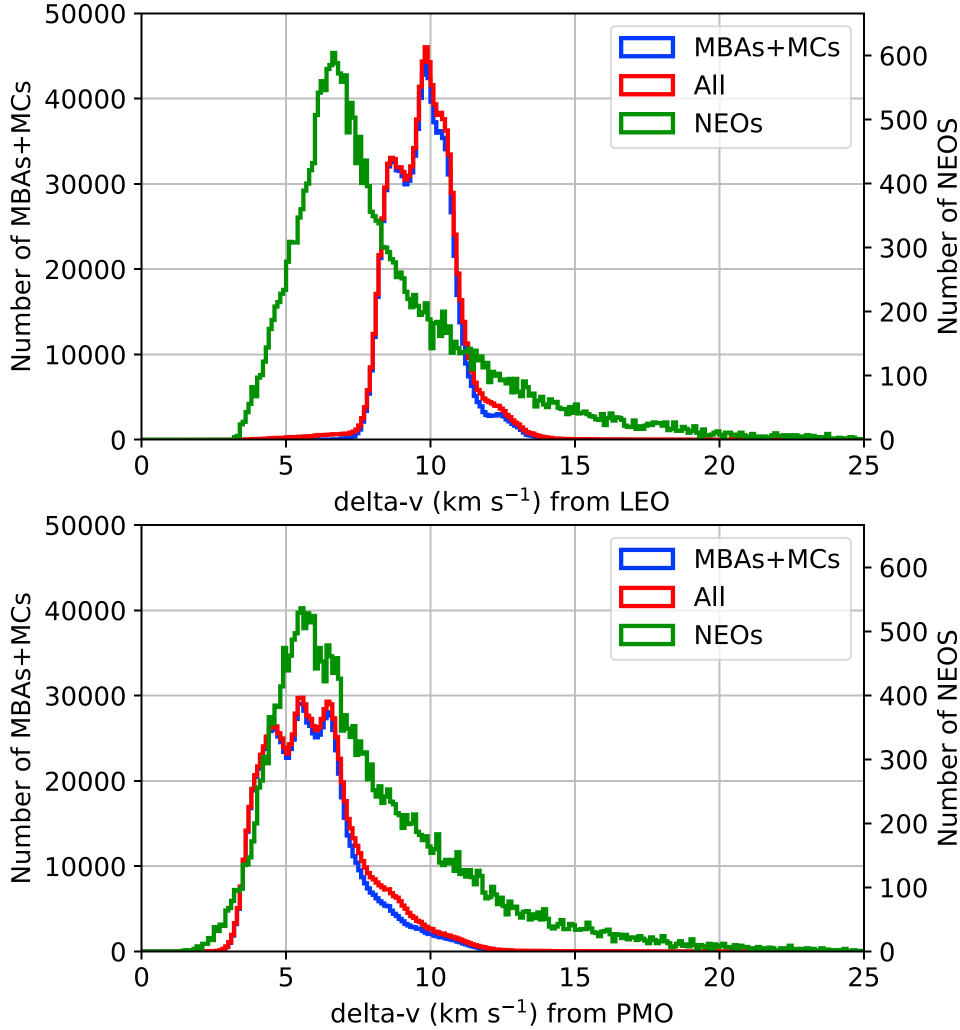

Fig. 2. The distribution of asteroid delta-v in the dataset. Left: from LEO; Right: from PMO. The NEO distribution has been rescaled by a factor of 75 on the right-hand y-axis for visibility. The histogram bin size is 0.1 km s^{-1}.

Python multiprocessing.Pool module. PARC, along with the results of this study, are available on GitHub at https://github.com/AT1555/PARC.

Our goal was to find the launch dates between 2050 and 2070 and the times of flight that provide the lowest delta-v for rendezvous with any asteroid from both Earth and Mars with single day precision in both launch date and time of flight. While PARC is reasonably fast and can calculate ~2200 delta-v's per second on a single CPU core, computing optimized delta-v trajectories for over 1.1 million asteroids for launch dates between 2050 and 2070 and sufficient flight times to account for different orbital alignments (as in Biktimirov et al., 2019) is a significant computational challenge for a modern workstation. Moreover, for any given asteroid, the rendezvous delta-v as a function of launch date and time of flight contains multiple local minima, typically showing periodicity as a function of launch date due to changing orbital alignments. As such, a simple minimization approach typically found a local minimum delta-v, not the global minimum delta-v. To address this challenge, we used a variable resolution grid based approach in 5 stages:

1. For a given asteroid and starting planet, we evaluated the delta-v using both the two burn and three burn schemes on a evenly spaced grid of launch dates from 2050 to 2070 in increments of 120 days and times of flight ranging from 10 days up to the orbital period of the object with the larger semimajor axis (the planet or asteroid) also at a 120 day resolution.
2. For the 10% of delta-v points on the Stage 1 grid with lowest delta-v we then reevaluated these points at 60 day resolution in both launch dates and times of flight.
3. For the 10% of delta-v points on the Stage 2 grid with lowest delta-v we again reevaluated these points at 30 day resolution in both launch dates and times of flight.
4. We next identified the point with the lowest delta-v in the Stage 3 data, and solved for rendezvous delta-v with 10 day precision in a 120 day by 120 day grid centered at this point.
5. Finally, we identified the point on the Stage 4 grid with the lowest delta-v and solved for rendezvous delta-v to single day precision on a 20 day by 20 day grid centered at this point. If the lowest delta-v in this final grid was at the edge of the grid, we repeated this step, re-centering the gird and the lowest delta-v point until a minimum in delta-v was found. Once a minimum was found, we identified it as the minimum delta-v for rendezvous and recorded the optimized launch date and time of flight.

This process requires on average a factor of ~5000 less computation time than evaluating on a full one day precision grid. We illustrate this

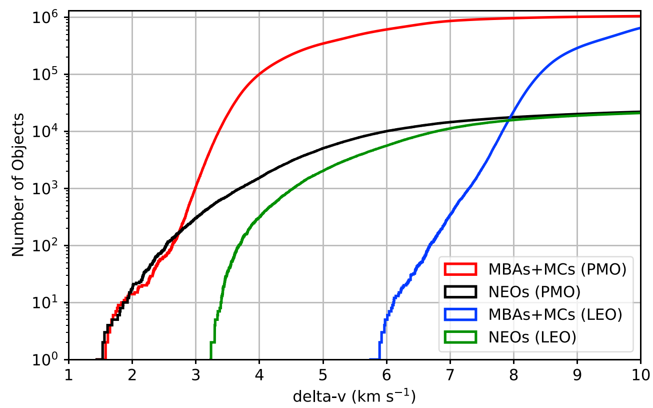

Fig. 3. Logarithmic cumulative distributions of the number of accessible MBAs + MCs and NEOs from LEO and PMO as a function of delta-v.

process in Fig. 1 for a rendezvous with Ceres starting at PMO.

We repeated this process for every asteroid in the MPC Orbit Database (MPCORB)[2] starting at both LEO and PMO. As of 2021, December 1, the dataset contained 1,152,875 asteroid orbits, including both the numbered objects and objects with only provisional designations. Both the numbered and provisional objects were included in this study. The total computation time was 55 h when running PARC on 16 threads of an Intel Xeon W-2145.

3. Results

3.1. Delta-V distributions

Fig. 2 shows the delta-v distributions for the entire MPC database as well as the MBAs and Mars Crossers (MBAs + MCs) and NEOs starting at both LEO and PMO. The median delta-v for MBAs + MCs is reduced by 4.0 km s^{-1} to 5.1 km s^{-1} from PMO from 9.7 km s^{-1} from LEO. This reduction is expected, as Mars is closer to the Main Belt ($a = 1.524$) than Earth and further out of the Sun's gravitational potential well. The multi-peak structure of the delta-v distribution is likely due to the non-uniform distribution of asteroid semi-major axes of MBAs + MCs, due in part to orbital resonances with Jupiter (Petit et al., 2002).

The distribution of NEO delta-v's in Fig. 2 has a median of 7.5 km s^{-1} from LEO, and 6.8 km s^{-1} from PMO. This, superficially surprising, reduced typical delta-v is due to the wide distribution of NEO semi-major axes. While all NEOs must by definition have a periapsis less than 1.3 AU, most are highly eccentric with a median eccentricity of 0.45. As a result of this, the median NEO semi-major axis is actually 1.70 AU, closer to that of Mars (1.524 AU) than that of Earth. Thus, typically, even NEOs are somewhat more accessible from a Martian starting orbit than from LEO.

Both distributions have small tails to their lowest delta-v. These tails are operationally important for mission design. We show these tails in Fig. 3 as a cumulative plot with a logarithmic axis to emphasize the behavior of the low delta-v tails of the distributions. These lowest delta-v asteroids, assuming they are of considerable mass and contain desirable material, will be the most accessible and easiest to reach for both exploration and mining. Future improvements in spacecraft engine technology will surely lead to gains in specific impulse (I_{sp}) which will directly increase the delta-v capacity of a spacecraft at a given mass. This I_{sp} gain might instead be used to transport larger masses at the same delta-v. Thus, even with highly efficient engines, the lowest delta-v targets will still be desirable in terms of deliverable/retrievable mass at a given mission budget.

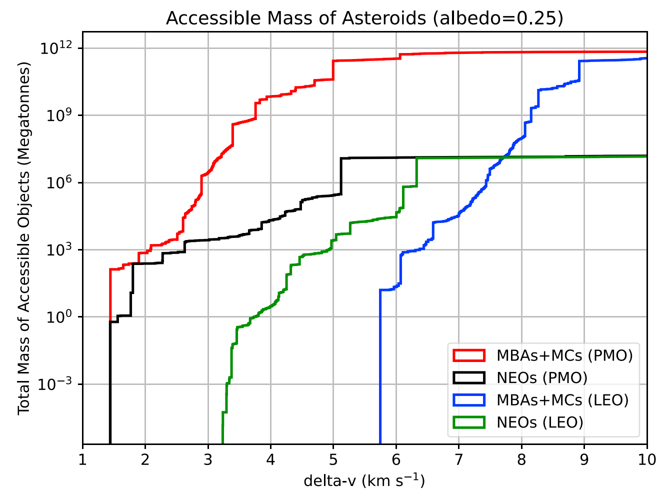

Fig. 4. Estimated cumulative distributions of accessible mass in MBAs + MCs and NEOs from LEO and PMO.

3.2. Accessible mass

For potential mining purposes, the accessible mass of asteroids is of particular interest. Most known MBAs + MCs are bigger than the largest NEO, (1036) *Ganymed*, at ~50 km diameter. Therefore, the accessible mass of MBAs + MCs increases more quickly than an equivalent number of NEOs at a given delta-v requirement.

To quantify this gain we constructed mass estimates using the reported absolute H magnitudes of asteroids in the MPC dataset. Following the procedure from the MPC[3] to convert absolute magnitudes to diameters, we assume an albedo for all asteroids of $p_v = 0.25$. In reality, asteroid albedos span a wide range from $\sim 0.05 < p_v < 0.3$ (Mainzer, Grav, et al., 2011). Asteroids with lower albedos will have larger actual volumes by a factor of $(4p_v)^{-3/2}$. We assume spherical shapes for the asteroids to estimate their volumes. As is well-documented in Carry (2012), asteroid density varies greatly with asteroid spectral type, mass, and volume with significant scatter in all of these metrics. Given these large uncertainties, we simply assume a universal asteroid density of 2.5 g cm^{-3} (2.5 tonne m^{-3}) based on the mass weighted average of the most massive known asteroids: Ceres, Pallas, and Vesta. We then calculate the estimated masses for each object. We show the distribution of accessible asteroid mass in Fig. 4.

The majority of the mass in Fig. 4 is due to Ceres, Pallas, and Vesta (at 6.06 km s^{-1}, 11.86 km s^{-1}, 5.00 km s^{-1} from PMO and at 10.33 km s^{-1}, 13.45 km s^{-1}, 8.92 km s^{-1} from LEO respectively) but operationally it is the low delta-v tails that are of particular interest. We find that PMO provides access to $\sim 7 \times 10^{15}$ tonnes of material within $\Delta v < 4$ km s^{-1}. Over 99.99% of this mass is in MBAs and MCs, while the NEOs form a near insignificant fraction (~0.005%). From LEO, only $\sim 3 \times 10^{6}$ tonnes of material are accessible within $\Delta v < 4$ km s^{-1} and are entirely found in NEOs. NEOs remain the most accessible targets from LEO up to a delta-v of 7.7 km s^{-1} at which they are overtaken by MBAs + MCs. However, from PMO, MBAs + MCs and NEOs start nearly equally accessible in number, but the larger masses of the MBAs + MCs immediately surpass the NEO mass at the same delta-v budget.

3.3. Orbital parameters of low delta-v asteroids

It is of interest to examine the orbital elements of the most accessible asteroids. We show the distribution of delta-v in (a, i) space in Fig. 5.

Clearly, the most accessible asteroids from either Earth or Mars are

[2] This dataset is available and updated daily at https://www.minorplanetcenter.net/iau/MPCORB/MPCORB.DAT.gz.

[3] https://minorplanetcenter.net/iau/Sizes.html.

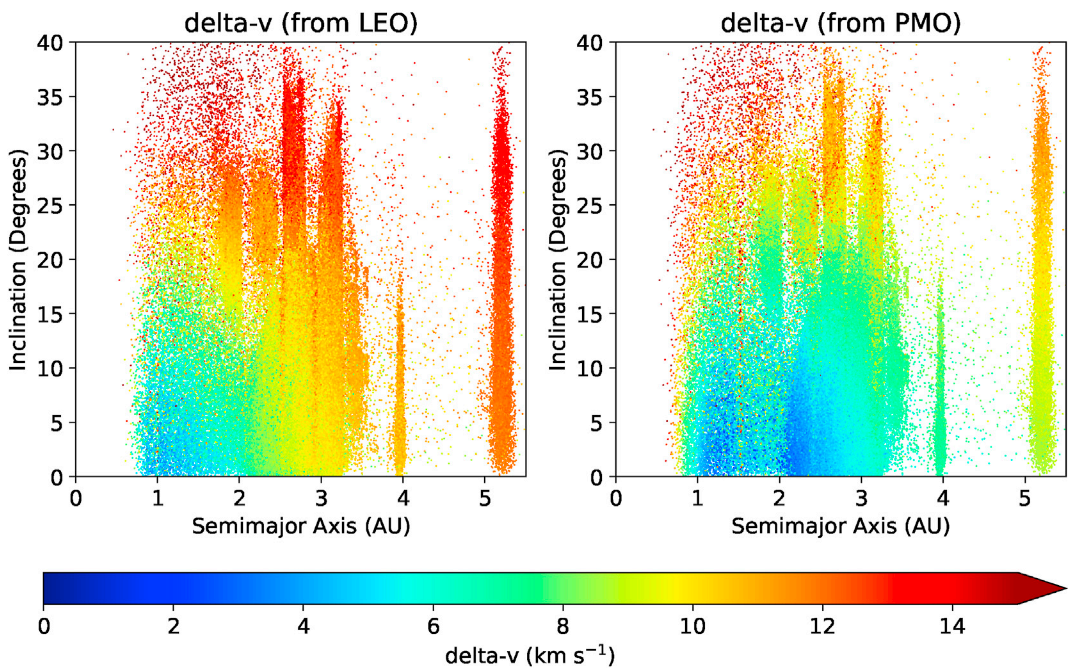

Fig. 5. Asteroid inclination (i) plotted against semi-major axis (a), with delta-v in km s^{-1} as a color scale. Asteroids with a delta-v of 15 km s^{-1} or greater are capped at 15 km s^{-1} on this plot. These objects make up <1% of the dataset.

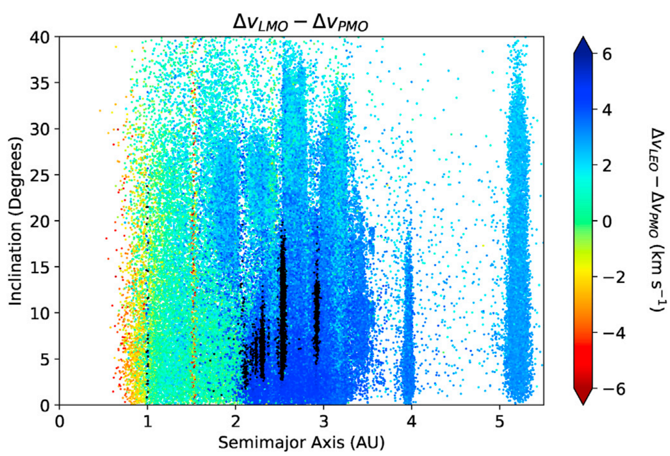

Fig. 6. Asteroid inclination (relative to the Earth's ecliptic i) plotted against semi-major axis (a), with the change in delta-v from starting at LEO to starting at PMO in km s^{-1} as a color scale. Colors red-ward of green indicate that starting at LEO provides a lower delta-v for rendezvous, while colors blue-ward of green indicate an advantage towards starting at PMO. Asteroids with ($\Delta v_{LEO} - \Delta v_{PMO}$) > 5.45 km s^{-1} (the delta-v necessary for a LEO to PMO transfer) are marked in black.

those with semi-major axes and inclinations most similar to those of each planet. Both starting approaches are biased against high inclination ($i <$ 15°) targets, especially at low semi-major axes ($a <$ 2 AU), where inclination changes are the most energetically costly.

Comparing the difference in delta-v based on starting planet for all targets in Fig. 6, it is clear that, with the exception of some asteroids with semi-major axes of 1 ± 0.5 AU, most asteroids are more accessible from Mars than from Earth. Some interesting exceptions are the Mars Trojans at a semimajor axis of ~1.5 AU (seen as a vertical red band at 1.5 AU in Fig. 6). These are particularly difficult to efficiently rendezvous with from a Mars orbit, as the transfer orbit must deviate from Mars' orbit to make up the difference in true anomaly between Mars and the target asteroid before restoring the Mars-like orbit upon rendezvous.

4. Costs and advantages of Mars orbit

4.1. Delta-v

The above distributions neglect the delta-v necessary to reach a Mars parking orbit starting from an Earth parking orbit. Using two burns, one to escape the Earth starting in a 400 km LEO parking orbit and establish a Mars transfer orbit ($\Delta v = 3.57$ km s^{-1}), and the other to circularize the resulting Mars capture orbit at the orbital height of Phobos ($\Delta v = 1.88$ km s^{-1}), results in a total LEO-PMO delta-v of 5.45 km s^{-1}. For almost all asteroids, adding this to the delta-v of accessing the asteroid from PMO will result in a larger total delta-v than simply accessing the asteroid starting from LEO. Including the 5.45 km s^{-1} investment in transferring to a Martian parking orbit, the median delta-v for accessing MBAs + MCs increases to 11.16 km s^{-1}, now greater than the median 9.73 km s^{-1} delta-v for direct access from LEO. This is expected, as entering, circularizing in, and exiting Mars' gravity well inherently wastes some energy and delta-v.

Whether the Phobos delta-v penalty is economically disadvantageous depends on the masses to be moved, both of raw and beneficiated (refined) ore, and of mining and processing equipment. If the beneficiating equipment is massive then the simplified raw material gathering spacecraft that will undertake the Phobos to asteroid journey may be of significantly lower mass.

If infrastructure were built for functions such as spacecraft maintenance and refueling for both mining and exploration missions or material processing and beneficiation then Martian orbit could be used as a beneficial forward operating base for asteroid exploration/mining. Those functions may justify the ~1.43 km s^{-1} median added cost in delta-v.

The Martian starting orbit is most preferred in the low inclination ($i <$ 5°) Main Belt (Fig. 6). In some cases, PMO offers improvements of >5 km s^{-1}. These MBAs + MCs are particularly interesting, as the savings of ~5 km s^{-1} nearly offsets the ~5.45 km s^{-1} cost of first traveling to PMO from LEO before rendezvousing with a target asteroid. Thus for these

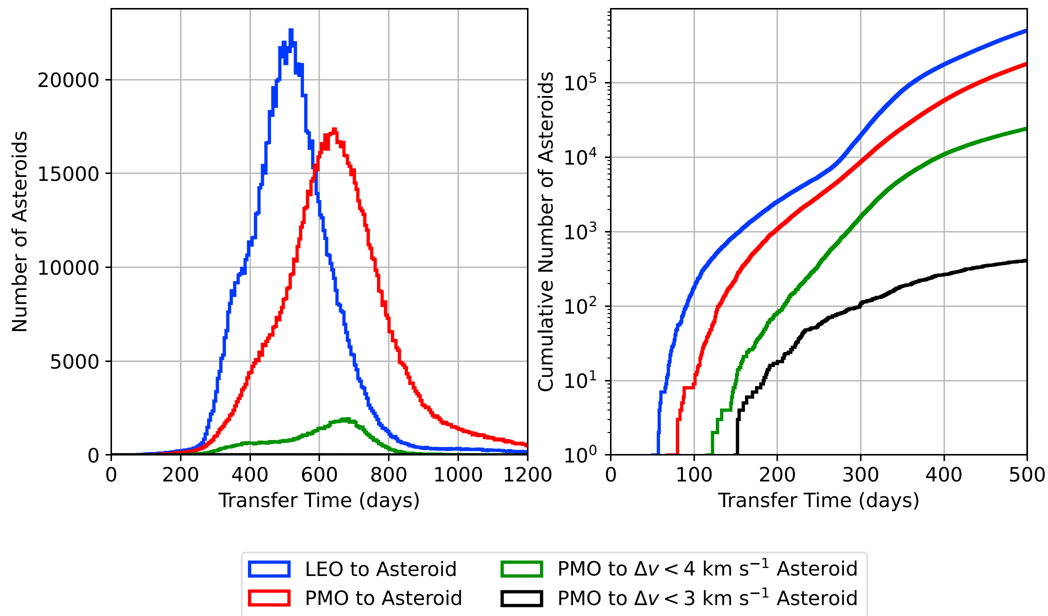

Fig. 7. Left: Asteroid rendezvous transfer times starting from LEO (blue), PMO (red), PMO for asteroids with $\Delta v < 4$ km s^{-1} (green), and PMO for asteroids with $\Delta v <$ 3 km s^{-1} (black) in 5 day bins. Right: Cumulative distribution of accessible asteroids as a function of rendezvous transfer times.

asteroids, stopping at a PMO forward operating base would add very little to the required mission delta-v. With the possibility of refueling in Mars orbit a reduced craft size and thus reduced mission cost, is both plausible and desirable. For this sizable subset of 3096 MBAs + MCs (with a total mass of 7.9×10^{13} tonnes and marked in black in Fig. 6) with a >5.45 km s^{-1} reduction in delta-v, the median delta-v from Mars is 4.83 km s^{-1} (or 10.28 km s^{-1} factoring in the LEO–PMO transfer delta-v).

4.2. Transfer times

When considering mission transfer times, the median LEO to MBAs + MCs transit time is 518 days and PMO to MBAs + MCs is 648 days. We show the distributions of transfer times in Fig. 7. The Mars to MBAs + MC transit times are longer that the Earth to MBAs + MC transits due to the naturally lower orbital speed of Mars and objects further from the Sun. These relatively long transfer times are a consequence of optimizing only for the absolute lowest delta-v transfers. For example: referring back to Fig. 1, the lowest delta-v transfer from PMO to Ceres has a transfer time of 517 days, a delta-v of 6.06 km s^{-1}, and launches in November 2054. However, this transfer time could be reduced to 399 days at the cost of an additional 0.52 km s^{-1} by launching in June of 2064. This is the shortest transfer time local delta-v minimum for Ceres for launches between 2050 and 2070. The transit time could be further reduced at the cost of rapidly increasing delta-v. While we do not examine transit time optimization in this work, such a study could be easily performed with PARC and a modified gridding and optimization scheme.

Taking into account the LEO to PMO transfer time (~255 days) in addition to the PMO to MBAs + MC transit gives a total median time of 903 days. While this is a comparatively long mission time, transit times could be reduced through more costly delta-v flight paths (as above). In the case of an established Phobos mining base, with a continuous flow of material between MBAs + MCs, Mars, and Earth, the transit time becomes less important.

5. Conclusions

We find that there is a far larger population of known asteroids accessible to current technology from Phobos orbit than from low Earth orbit, by a factor of 300 in number and a factor 10^9 in mass for a delta-v of 4 km s^{-1}. Although there is a delta-v penalty of ~5.5 km s^{-1} for going into Phobos orbit from LEO, a sizable population of 3096 Main Belt asteroids is known for which the Phobos delta-v gain over LEO is larger than that. Phobos is a convenient site for emplacing massive ore-refining equipment. Phobos has properties that aid in extracting ore from raw asteroid material, as it provides some gravity, an inertial platform, and radiation shielding. Phobos may then serve as a useful forward operating base for the exploration and mining of the Main Belt. The presence of large-scale operations in Mars orbit may also lead to routine access to Mars' surface.

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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