Near Earth Asteroids:The Celestial Chariots

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Abstract

In this paper we put forward a proposal to use Near Earth Objects as radiation shield for deep space exploration. In principle these objects can provide also a spacious habitat for the astronauts and their supplies on their journeys. We undertake also a detailed assessment of this proposal for a mission from Earth to Mars.

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1 Introduction

In the last half-century, humans have set foot on the moon and, as a result, deep space travel seems to be within Humanity's reach. However, there are many issues that must be resolved before space travel to other objects in the solar system can become a reality. Examples of these issues include radiation in space, physiological effects of zero gravity, power generation, and propulsion methods.

In this paper we put forward a novel proposal that can mitigate the dangers that radiation can pose to space travel. The basic idea behind this proposal is the use of Near Earth Objects (NEOs) as a temporary shelter from radiation for astronauts on deep space missions, like a voyage to Mars.

Just as fire can be both dangerous and beneficial, the NEOs that pose a danger to Humanity on Earth can be used as "Celestial chariots." By protecting the astronauts from radiation, and providing spacious housing and storage facilities, long journeys into deep space become possible.

We begin with a general overview of radiation in space and its effects on exposed humans. Various strategies to protect astronauts from these harmful effects are then described. We concentrate on the use of NEOs a radiation shields, and we put forth a proposal using them on a trip to Mars and the feasibility of such a proposal. We conclude by discussing ideas that, if realized, would greatly increase the likelihood and the benefit of NEOs as radiation shields.

To examine this idea in detail, one has to choose the most suitable NEO out of the ten thousand known that could be utilized to travel between Earth and Mars. The chosen NEO must be of sufficient size and material to properly shield its cargo of humans and supplies from the radiation in space. In addition, we examine the possibility of "domesticating" an asteroid by manipulating its orbit. To protect the astronauts on their journey, a habitat can be built in the NEO in which a manned crew would ride safely from Earth to Mars. The crew would then exit the NEO upon approaching Mars.

2 Radiation and Its Effects

Short wavelength radiation, such as X-rays and Gamma rays, is harmful to living organisms. On Earth, protection is provided from these harmful effects by the Van-Allen belts, Earth's magnetic field, and the atmosphere. In space, however, there is no such shielding.

Radiation in space is made up of Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs), which are atomic and subatomic particles accelerated to (very) high energy levels. Another source of radiation, though usually ignored, is known as secondary particles [1]. These high-energy radiation sources pose a major threat to astronauts as they can cause cancer and genetic mutations. Humans outside the Earth's protective shield must use other means to protect themselves from radiation's ill effects.

2.1 Galactic Cosmic Rays

GCRs originate from outside our solar system and have particle energies known to peak around 1 GeV within the solar system. Approximately 98 percent of these particles are protons or heavy ions which possess a high linear energy. This linear energy enables these particles to deeply penetrate almost any shielding. The collision of the radiation with a shielding material is likely to generate secondary particles, increasing the total amount of shielding needed to maintain a safe environment for life.

GCR radiation levels within the solar system vary with the natural solar cycle. The fluctuation of the Sun's magnetosphere and material output changes the amount of GCRs deflected away from the core of the solar system. [2]

2.2 Solar Particle Events

SPEs are made of solar flares and coronal mass ejections (CMEs), both of which spew ionized gases and radiation from the Sun. Large events of this nature are rare, however their frequency depends upon the sun's 11-year activity cycle.

Impulsive flares are short lived, on the order of hours, but release large amounts of electron radiation. They are not overly dangerous to space travel to other planets as they are emitted in a range from 30 to 45 angles in solar longitude and leave the ecliptic plane quickly.

CMEs are much longer lived than flares, lasting days, and are characterized by a high proton flux on the order of 10^9 particles per square centimeter. They can erupt anywhere from the Sun's surface and reach Earth and other planets, impacting spacecraft and space-based resources en route to or in orbit around these planets.[3]

2.3 Impact of Radiation on Living Organisms

Radiation in the International System of Units (SI) can be measured in Sieverts (Sv). The Sievert is the equivalent absorption of one joule of energy by one kilogram of matter. This means that it represents the biological effects of ionizing radiation by taking into account the biological context.

A human exposed to more than 1 Sv will suffer varying illnesses including leukopenia and other immune system-impairing conditions. A radiation dose greater than 8 Sv will be fatal to humans within days, as they succumb to organ failure and severe burns. An astronaut on board a spacecraft exposed to a solar flare or CME would likely be killed.

Even on spacecrafts without humans, radiation can pose a hazard to the mission. Space radiation can interact with the spacecraft electronics, damaging or destroying them. It affects computer operations and stored data by flipping the charge of bits between positive and negative. This happens when a charged particle impacts a bit, it flipping the charge and corrupting the data. Under extreme radiation, like the particle flux of CMEs, the information can be completely corrupted.

Currently, there are two main ways to internally shield electronics. By using older chip designs with larger gaps between bits, it is less likely that a particle will flip multiple bits, minimizing the damage. Additionally, the CPU equivalent of lightning rods can be built into the vulnerable circuitry to redirect the incoming radiation into less-critical areas. An external method to shield the electronics involves physically encasing the computers with protective material, but at the cost of adding mass to the mission. It is desirable to find the lightest and most cost effective shielding.

2.4 Radiation Shielding

Radiation shielding is measured in "half thickness", which is the amount of material needed to reduce the incoming radiation in half. By overlapping several half thicknesses, incoming radiation can be further reduced and a safe environment can be established. If we know the expected radiation levels and the material properties of our shield, we can determine how much shielding is needed. The following equation can be used to determine the half thickness, where μ is the material's bulk mass absorption coefficient and ρ is the material density.

$$t_{1/2} = -\frac{\ln(0.5)}{\mu\rho}$$

Determining the shielding thickness needed is simple in concept, but requires knowledge of High Energy Particle Physics and Material Science. The interaction between the incoming radiation with the shielding materials needs to be accurately known.

To keep the astronauts healthy throughout their travel in space, it is desirable to keep the radiation levels in the spacecraft as close to Earth-level as possible. There are established guidelines published by the NCRP (National Council on Radiation Protection) which NASA currently uses to determine what the astronauts on the ISS can safely experience.[4]

2.5 Radiation Blocking Materials

Shielding materials should be selected based on several criteria including half thickness and total mass. The ideal material would be both lightweight and have good deflection properties against radiation particles. Lead is the de-facto shielding material on Earth, but it does not meet our criteria due to it's large mass. Even though it will not be used for spacecraft shielding, it will be used as a basis for comparison with the other materials because it is a common shielding material.[4] Below, in Table 1, we provide a list of materials that could be used to protect against radiation in future space missions. In this table we explain what kind of material it is, how it can be used against radiation, and how much of the material is required.

Table 1: A Sample of Radiation Protective Materials

Protective Material	What is it	How does it work against radiation	How much is required
Lead	Chemical element with atomic number 82	It's extremely high density provides shielding from radiation particles	10cm for a reduction of 1000x
Polyethylene (Demron)	Most commonly used plastic for commercial products A chemically synthesized polymer with high amounts of hydrogen -Demron is polyethylene between two layers of fabric	Demron is lightweight, flexible and contains proprietary materials that block radiation.It can be treated like a fabric for cleaning, storage, and disposal purposes	A thickness of 2.7 cm (72 layers) and 29 cm (240 layers) of Demron would be required for a two factor and ten factor reduction in transmission
Boron Nitride Nanotubes	An equal chemical combination of both Boron and Nitrogen nanotube containing Boron Nitride	Due to its light nucleus, can successfully absorb harmful neutrons in secondary radiation. Additionally if used in the development of a space shuttle, this can further decrease the harm of radiation exposure for astronauts.	Approximately 1.5m is needed to reduce the effective dose rate (Eiso) by 45-48%
Electrostatic Shielding & Carbon Nanotubes	A material capable of blocking the effects of an electric field, while also allowing the passage to magnetic fields.	The use of conductive materials such as carbon-nanotubes (CNTs) can conduct enough energy to generate an electrostatic shield capable of blocking all incoming ion particles	Several feet of carbon a nanotube are required to shield against radiation
C60 (Buckminster-fullerene)	A spherical fullerene molecule with the formula C60 with a cage-like fused ring structure	Provides potential benefits against radiation if used as an antioxidant drug	TBD, more research needs to be done to determine appropriate doses

3 Near Earth Objects

Near Earth Objects (NEOs) are defined as any object that passes within 0.3 AU of Earth at some point in their orbit around the Sun. These include, but are not limited to, asteroids and dead comets. NEOs pose a danger to humanity on Earth as even the smallest NEO impact can release as much energy as a nuclear weapon or volcanic eruption. The Chelyabinsk Meteor that struck Russia on February 15th, 2013, was approximately 18 meters in diameter and generated nearly 440 kilotons of TNT. The threat of NEOs to humanity is very real, but what if they could be tamed and used for space travel?

3.1 NEOs for Radiation Protection And Space Travel

We propose to use NEOs for transportation within the solar system. With proper asteroid selection and preparation, it will be possible to take advantage of their material properties to protect the astronauts from space radiation. Other benefits of using NEOs will be spacious living quarters and expanded storage facilities for food, water and medical and scientific supplies. Larger crews can thus be supported, which will allow for social interaction during the long voyage and help the psychological well-being of the crew. For the purposes of explaining our proposal, we shall use a mission to Mars as a case study.

3.2 The basic Mission Profile

1. Identify NEOs that meet orbital requirements to pass Mars and Earth.
2. Determine NEO composition through physical landing, practicing orbital maneuvers.
3. Prepare NEO for habitation through robotic missions.
4. Land a crew on board NEO when habitation is completed and the asteroid is passing Earth en-route to Mars.
5. Travel to Mars inside NEO and leave when at Mars.

The implementation of this program is not simple. Although we have the technology to precisely calculate the orbits of NEOs, at present, it is quite difficult to determine if a particular NEO will be suitable as a radiation shield.

Furthermore, efficient methods have to be developed to prepare an asteroid for habitation. Below, we propose some ideas to reduce these complications, including changing the trajectory of asteroids. While these are all obstacles to the success of our vision, we believe that they are not insurmountable.

These preparations will need to be done ahead of time through robotic missions. Likely, a single launch or quick series of launches will transfer all the materials needed for the construction. Until the asteroid passes close to Earth again, the robots will build the habitable and radiation shielded volume. This allows for astronauts to simply land on the asteroid and have everything prepared. Additionally, it will be needed to plan for the return trip.

3.3 Advantages of Using NEOs

One of the consequences of using a conventionally shielded spacecraft is the large amount of mass that must be put into space. The cost of doing this behooves mission planners to design the interplanetary spacecraft with longevity in mind to reduce the need for expensive launches. However, long-term operation in high-radiation environments is dangerous, as radiation embrittles metals over time. This can best be seen in nuclear submarine reactors, where thirty years of service takes its toll on the reactor walls. Metal embrittlement and fatigue are a major concern for conventional spacecrafts where the interior has to be pressurized. However, this issue becomes moot if NEOs are used. While aluminum and other materials might be needed to construct the living quarters, they will be shielded by the bulk of the asteroid, and not weaken from radiation. Additionally, building inside the NEO allows for pressurization stresses to be spread into the NEO, reducing the stresses in the construction material.

Furthermore, one of the most dangerous physical threats to spacecraft, micro impacts, can be all but eliminated using NEOs. Small, high velocity debris generated in collisions can rupture conventional spacecraft. They are extremely hard to detect due to their size, but can vent the spacecraft's atmosphere into space, killing its crew. Nestled deep inside an NEO, micro impacts will not be able to penetrate far enough to be a threat to the crew.

3.4 Planning a Mars Mission

There is a lot to consider when constructing a mission to Mars using NEOs as transportation and radiation protection. Due to the large amount of unknown data, we cannot be certain that a given solution will work. However, we believe that the solution we have provided is flexible enough to accommodate the unexpected.

3.4.1 Enumeration of Asteroids

Selecting the right NEO out of the tens of thousands in orbit around the Sun is a daunting challenge. We shall limit the search to asteroids, as they are more likely to provide the radiation shielding we require compared to the other objects. From the more than 9,500 asteroids presently identified by NASA and other Space Agencies, our asteroid will have to meet the following criteria.

1. Must approach Earth and Mars' orbits and meet other requirements to improve crew transfer and safety.

2. Must be large enough and of the right composition to provide adequate shielding.

3. Must be small enough to be sufficiently movable to fine-tune the orbit. Our target size for such an asteroid is approximately 100 meters in diameter.

Our target size for such an asteroid is approximately 100 meters in diameter. This offers us the highest likelihood that we will have enough shielding, living space, and it will be small enough to move. Unfortunately, current detection methods are not accurate enough to detect asteroids 100 meters in diameter of less, and future satellite asteroid observation missions should be conducted to increase the likelihood of finding ideal asteroids. Infrared telescopes would be ideally suited for our purposes as they can sometimes identify the composition of the asteroid using spectrology.

3.4.2 Orbital Criteria

Even if we find an asteroid with a perfect material composition for radiation shielding, it means nothing if that asteroid does not fly by Earth and Mars on a regular basis. Therefore orbital criteria are an essential part of selecting asteroids. To reduce the amount of orbital manipulation required for each potential asteroid, those closest to Earth, which also intercept Mars' orbit, will be examined. Their perihelion should be within 0.05AU of Earth's orbit and their aphelion should extend to between Mars perihelion and aphelion, a range of 1.4 to 1.7 AU. The aphelion of their orbits should not extend beyond 1.7 AU to avoid a collision with another asteroid in the Asteroid Belt, thus drastically altering their orbit and making them useless for our purpose. These parameters reduce the number of Near Earth Object asteroids from over 9500 to around 200.

A final orbital consideration is the inclination of the asteroids orbits relative to Earth and Mars. In an Ecliptic plane reference frame, which passes through the Sun and Earth orbit, Mars orbit has an inclination of -1.8 degrees. In order for Asteroids to approach both Earth and Mars, they must orbit in between the planets inclination angle. For simplicity, we shall assume that we can manipulate the inclination angle of those asteroids nearest to the ideal orbit in such a way that they will precisely intercept the planets. By limiting our search to +/-10 degrees from the Ecliptic plane, the number of potential asteroids is refined to 43 (these are the highlighted asteroids in the Appendices). A complete list of known asteroids and their orbital parameters is available in Ref 17. Unfortunately, not much, if anything is known about their physical properties and currently we can only identify potential asteroids by their orbit.

An artistic conceptual trip to Mars using NEOs is attached at the end of this paper

3.4.3 Asteroids Composition

Asteroids that are classified as NEOs are broken into several categories based on their orbital path and material composition. One particular class of NEOs, known as Chondrites, are made of iron, water and carbon. Based upon infrared spectrology, NASA estimates that these asteroids are approximately 88 percent iron, making them an ideal radiation shields from a material standpoint. However, since iron is difficult to dig into, other asteroids that have a looser, or less-dense composition might be more suitable. With reduced density, they would have to be bigger to account for the difference in half thickness, but in space size doesn't matter. If the asteroid's mass is lower it will require less work to change its orbit.

Iron is the second best metallic element used to protect against gamma radiation being only second to lead. It only takes 4 inches of Iron to reduce gamma radiation damage by a factor of 10, whereas it takes 24 inches of water to reduce the damage by the same amount. Drilling down 340 feet of iron would reduce radiation damage by a factor of 1 million. The optimal choice of an NEO for mission purposes will need to take into account other properties of NEOs, such as their temperatures.

3.4.4 The Unknowns

While an asteroid may fit the orbital requirements for use in a manned mission, if it is incapable of shielding astronauts from radiation, it is useless. Not much is known about the material and physical makeup of the vast majority of asteroids. Therefore the necessary shielding thickness cannot be computed to construct safe living spaces on board. Experiments performed on samples of each asteroid, can provide the necessary data.

To precisely identify how much shielding is needed, samples of asteroids need to be collected and analyze. Using instruments similar to the Curiosity Rover x-ray spectrometer and Laser Induced Breakdown Spectroscopy system, a probe exploring each potential asteroid can relay the exact material composition and makeup to Earth.

Attempting to rendezvous with the most promising asteroids for sample analysis is not a new idea. In 2000, Japan launched the Hayabusa mission which landed on 25143 Itokawa and was able to retrieve samples and return them to Earth.[7] Complications in the attempts to collect the samples leads us to believe that a spacecraft designed to stay with the asteroid and analyse it would be better. It would allow for more information to be collected about the asteroid and possibly begin mapping the surface aid in construction.

4 Futuristic Vistas

4.1 Orbit Modification

Making feasible use of asteroids for transportation will often require that the asteroid's current orbit be modified in order to make the transfer between Earth, Mars, and the asteroid more convenient. Unfortunately, this process requires extensive use of impulsive thrusting over the course of several orbits. The thrusting will have to be done over perigee and apogee centered burn-arcs, possibly at constantly changing thrust angles. Furthermore, concurrent changes in the asteroids apogee, perigee, eccentricity, and inclination angle will have to be made in order to affect the orbit change in a reasonable amount of time and minimum amount of resources.[8] Due to the difficulty in analyzing such a scenario the specifics will not be covered in this paper. However the nature of the propulsion that should be used in this process can be analyzed. The basis for analyzing different propulsion methods lies in an equation of motion derived from the Reynolds transport theorem. This equation is:

$$\left(M - \frac{dm}{dt}\right) A = \frac{dm}{dt} V$$

Where:

- M is the total mass of the craft (the asteroid)
- A is the acceleration of the craft
- t is thrust time
- $\frac{dm}{dt}$ is the mass flow rate of the propulsion system.
- V is the propellant velocity of the propulsion system

The focus will be on the right half of the equation, $\frac{dm}{dt}V$, which is equal in magnitude to the thrust force on the spacecraft. These two parameters, the mass flow rate $\frac{dm}{dt}$, and the propellant velocity (V), can be used to evaluate the advantages and disadvantages of propulsion methods. The advantage of a high V is that more energy is imparted per propellant mass, meaning that in a situation where propellant mass is limited, such as long distance missions, more total energy can be imparted. High V systems tend to have very low $\frac{dm}{dt}$, but also very low thrust. However many high thrust propulsion technologies have low V, making them mass inefficient and suitable only for short missions.

Since propellant will be brought to the asteroid very infrequently due to the rarity of close approaches and the difficulty of coordinating long distance shipments, the propulsion method used on the asteroid will have to be as propellant mass efficient as possible. To this end a high propellant velocity is necessary, which can be found in ion engines.

An ion engine generates thrust by accelerating ions to high velocity and expelling them out of the rear of the spacecraft. The gas is typically an inert gas such as Xenon to avoid unwanted reactions. [10] There are two ways to accelerate the gas. First is the electron bombardment method where the engine bombards the propellant with high-energy electrons, knocking Xenon's valence electrons free. [11] Second is the electron cyclotron resonance method, which excites the electrons in the gas via microwaves and magnetic fields. [11] Once ionized, the gas is accelerated out of the engine by electrostatic forces generated by a positively charged grid at the beginning of the flow chamber and a negatively charged grid at the end. [12]

Some high velocity ion engines expel their propellant at speeds in excess of 90,000 m/s, but produce minimal thrust and expel very little propellant. [13] Atypical modern ion engine thrust is a mere 0.5 N, but fortunately higher thrust engines are in development.[16] One such project, the High Power Electric Propulsion project has developed a 40 kW engine, more than 19 times more powerful than the engine used by Deep Space. [17] [18]. Furthermore, 200 kW configurations have been suggested, which would boost thrusts up to 18 N, propellant velocities of 40,000 m/s or higher, and with a low mass flow rate between 100 and 1200 mg/s.[19] Despite the power increase, they retain a power efficiency of upwards of 60% and a calculated thrust to mass flow ratio of up to 50000 N*s/kg.

If several of these higher thrust ion engines are placed on the asteroid they will allow for the asteroid's orbit to be modified with low propellant and energy costs. The main objective of these orbit manipulations will be to place the asteroid into a mildly elliptical orbit which will travel from Earth to Mars in about 200-250 days. This will require the asteroid's velocity to be approximately 25 kilometers per second, an easily attainable figure. If the engines are thrusting for years on end.

4.2 NEO Domestication

The solution to the radiation problem that we are proposing in this paper relies on having a collection of easily accessible domesticated NEOs, which we have implicitly assumed to exist in our presentation. However, this is where the complexity of our solution lies, and this is what will determine the likeliness of using NEOs as transportation vehicles within the solar system.

Domesticating a single NEO involves modifying the NEO orbit and excavating a radiation-protected area in its body. As previously discussed, it is plausible to modify an NEO orbit with ion thrusters. Further research will need to be done in order to determine the best methods to create a radiation-protected habitat, but we can put forth here the essential requirements. Using advanced robots that are physically and electronically hardened to survive in deep space, the selected asteroid will be prepared by drilling away material to construct the shielded living quarters for the crew. Being essentially stranded on the asteroid with no material support and little communication, the robots will have to be rugged, capable of repairing themselves, and completing the complex operations demanded of them with minimal error.

The vision we have is not just one domesticated asteroid. We believe that a few dozens will be necessary in order to make frequent trips to and from Mars due to their long orbital periods. Great care should be taken when creating this group so that the asteroids will not be on a collision course with Earth and survive for centuries to make the most of our investment in converting them.

4.3 Time of Flight

When dealing with radiation and space travel, time is in the essence. It dictates how much shielding, food, water and fuel is needed for the mission, and therefore something that we should be aware of during mission planning. Trying to calculate the close approaches between the asteroid and each planet is difficult when the different orbit periods and angle differences are considered. In some cases it might be necessary for the crew to stay on board the asteroid for several years while the planets move into position. On the other hand, if everything went according to plan, an asteroid could take a direct route between Earth and Mars.

With orbit modification, this direct route could become more routinely possible if enough asteroids were domesticated and enough orbit modifications done. In this manner, the travel times between the planets would be around 200-400 days. Most of the asteroids that met our orbital criteria typically orbited the Sun in 500 to 650 days and they intersect each orbit in two places, creating two transfer points from planet to asteroid or vise-versa.

Getting to and from the asteroid is another concern for astronauts, as their exposure to radiation is greatest during this transfer. Given that the asteroid cannot come into Earth's gravitational influence, the astronauts must exceed Earth's escape velocity of 11920 m/s. From launch, it should only take a few days to leave Earth's gravity well and rendezvous with the asteroid. The total time of flight for this portion of the mission is solely dependent on how close the asteroid is to Earth. With precise orbit modifications the asteroids can be put a safe distance from Earth's gravity, but not too far away that it risks the health of the astronauts. Leaving from Mars should be very similar to this process, but quicker as Mars gravity is weaker than Earth's

Leaving the asteroid will be different than landing on it, as the escape velocities are thousands of times lower than any planet. In theory this transfer should be a simple reverse of leaving a planet, but this time, the astronauts have to enter the atmosphere and precisely land at their target. With proper care and planning, this can be done, but it will not be simple.

4.4 Returns on Investment

Domesticating a fleet of asteroids will not be cheap, nor perhaps cost effective in the short term, but it is the long-range returns that make NEO transportation worthwhile. The international Space Station has orbited for more than 15 years and will continue doing so for many years to come, but at some point the space station will reach the end of it's life and be retired. The data gathered onboard the ISS cannot be collected anywhere else, making it well worth the 150 billion dollars it has cost so far. Thus, the domesticated asteroid orbiting around the Sun will be worth the trillions invested in them as they serve humanity. The benefits of such a mission extend much further beyond the simple monetary, scientific, and humanitarian returns it will generate. It offers a way to protect Earth and humanity. To date, Earth has no defense against asteroids and comets and we bear the scars of massive impacts in the past. The likelihood of such a collision is relatively admittedly small, but using the orbit modification techniques developed to domesticate the asteroids, humans can remove the most dangerous NEOs that threaten Earth and humanity. The safety of our planet and continuation of our species is worth any price.

5 Conclusion

We believe humanity is on verge of new era in which humans will expand their habitat to other celestial bodies. The advent of this new era is driven by the combination of human curiosity and drive to einsure human survival. Radiation poses one of the greatest threats to the successful expansion of our race throughout the solar system and beyond. Without proper protection from this hazard, future space travelers may either die or be genetically altered. This paper put forward the idea that the use of NEOs is a possible solution for protecting humans against radiation en route to a new planet or celestial object. This idea should be investigated further in the future as a supplement to other radiation protection efforts.

Although NEOs have primarily been viewed as hazardous to Human survival on Earth, we have developed a different perspective allowing us to take advantage of the properties that make them dangerous. In the same way that fire, an incredibly destructive force, was mastered in order to advance and expand human society on Earth, we believe that NEOs can be used are needed to expand human society across space.

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Appendix A: NEAs in Near-Hohmann Orbits to Mars' Aphelion

NOTE: Due to a lack of information on the physical properties of the asteroids listed in this table, only their orbital parameters are included. Information from the NASA JPL Small Body Database and the IAU Minor Planet Center.

Asteroid Name	NEA Group	Aphelion (AU)	Perihelion (AU)	Semi-Major Axis (AU)	Eccentricity	Orbital Period (Days)	Ecliptic Inclination (°)
25143 Itokawa (1998 SF36)	Apollo	1.6952	0.9532	1.3242	0.2802	556.2141	2.4283
(2004 NK8)	Apollo	1.7000	0.9541	1.3270	0.2811	557.9741	-4.6042
(2009 SN103)	Apollo	1.6442	0.9542	1.2992	0.2656	540.5227	-3.3692
(2012 SG32)	Apollo	1.6450	0.9569	1.3009	0.2644	541.6032	9.9726
(2008 UR)	Apollo	1.6705	0.9585	1.3145	0.2708	550.1119	5.0451
(2000 CM33)	Apollo	1.6825	0.9628	1.3227	0.2721	555.2264	9.7228
(2010 SV15)	Apollo	1.6772	0.9642	1.3207	0.2699	554.0215	-1.5370
(2007 FB)	Apollo	1.6590	0.9675	1.3133	0.2633	549.3181	9.1710
(2010 VO21)	Apollo	1.6722	0.9816	1.3269	0.2602	557.9055	4.7263
(2009 DC12)	Apollo	1.6734	0.9897	1.3316	0.2567	560.8456	-4.0678
(2004 BV18)	Apollo	1.6738	0.9951	1.3345	0.2543	562.6799	-2.8155
(2008 TT26)	Apollo	1.6915	0.9993	1.3454	0.2573	569.6073	-5.6807
(2003 XH10)	Apollo	1.6445	0.9996	1.3221	0.2439	554.8595	-2.6101
(2006 BQ7)	Apollo	1.6936	1.0003	1.3469	0.2573	570.5934	-4.9148
(2009 SL)	Apollo	1.6999	1.0004	1.3502	0.2590	572.6344	2.9294
(2012 VD6)	Apollo	1.6860	1.0011	1.3435	0.2549	568.4227	-1.1708
(2010 FC)	Apollo	1.6485	1.0104	1.3295	0.2400	559.5186	-0.5002
(2003 YN1)	Apollo	1.6604	1.0106	1.3355	0.2433	563.3374	2.4949
89136 (2001 US16)	Apollo	1.6984	1.0129	1.3556	0.2529	576.1184	5.6500
(2010 XD)	Amor	1.6496	1.0178	1.3337	0.2369	562.1876	0.9665
(2008 SO)	Amor	1.6421	1.0198	1.3309	0.2338	560.4387	-0.0169
(2010 PS66)	Amor	1.6696	1.0207	1.3451	0.2412	569.4517	-6.0393
(2009 SW171)	Amor	1.6417	1.0208	1.3312	0.2332	560.6362	-4.0976

Asteroid Name	NEA Group	Aphelion (AU)	Perihelion (AU)	Semi-Major Axis (AU)	Eccentricity	Orbital Period (Days)	Ecliptic Inclination (°)
(2008 CB175)	Amor	1.6688	1.0237	1.3462	0.2396	570.1504	1.9534
(2004 FK2)	Amor	1.6410	1.0245	1.3327	0.2313	561.5753	4.2837
(2006 CL9)	Amor	1.6648	1.0276	1.3462	0.2367	570.1282	-4.2198
(2001 SZ169)	Amor	1.6410	1.0277	1.3344	0.2298	562.6249	-0.8266
(2010 VA1)	Amor	1.6601	1.0345	1.3473	0.2321	570.8109	4.5975
(2011 WB96)	Amor	1.6806	1.0397	1.3601	0.2356	578.9813	9.7771
(1987 WC)	Amor	1.6804	1.0437	1.3621	0.2337	580.2281	8.6878
(2008 HS3)	Amor	1.6562	1.0456	1.3509	0.2260	573.1254	1.0228
(2005 HB4)	Amor	1.6640	1.0457	1.3548	0.2282	575.6041	-4.6277
(2011 SC16)	Amor	1.6447	1.0461	1.3454	0.2225	569.6181	-0.4780
152787 (1999 TB10)	Amor	1.6785	1.0477	1.3631	0.2314	580.8903	8.7973
(2011 WD)	Amor	1.6721	1.0494	1.3608	0.2288	579.3922	-1.4705

Appendix B: NEAs in Near-Hohmann Orbits to Mars' Perihelion

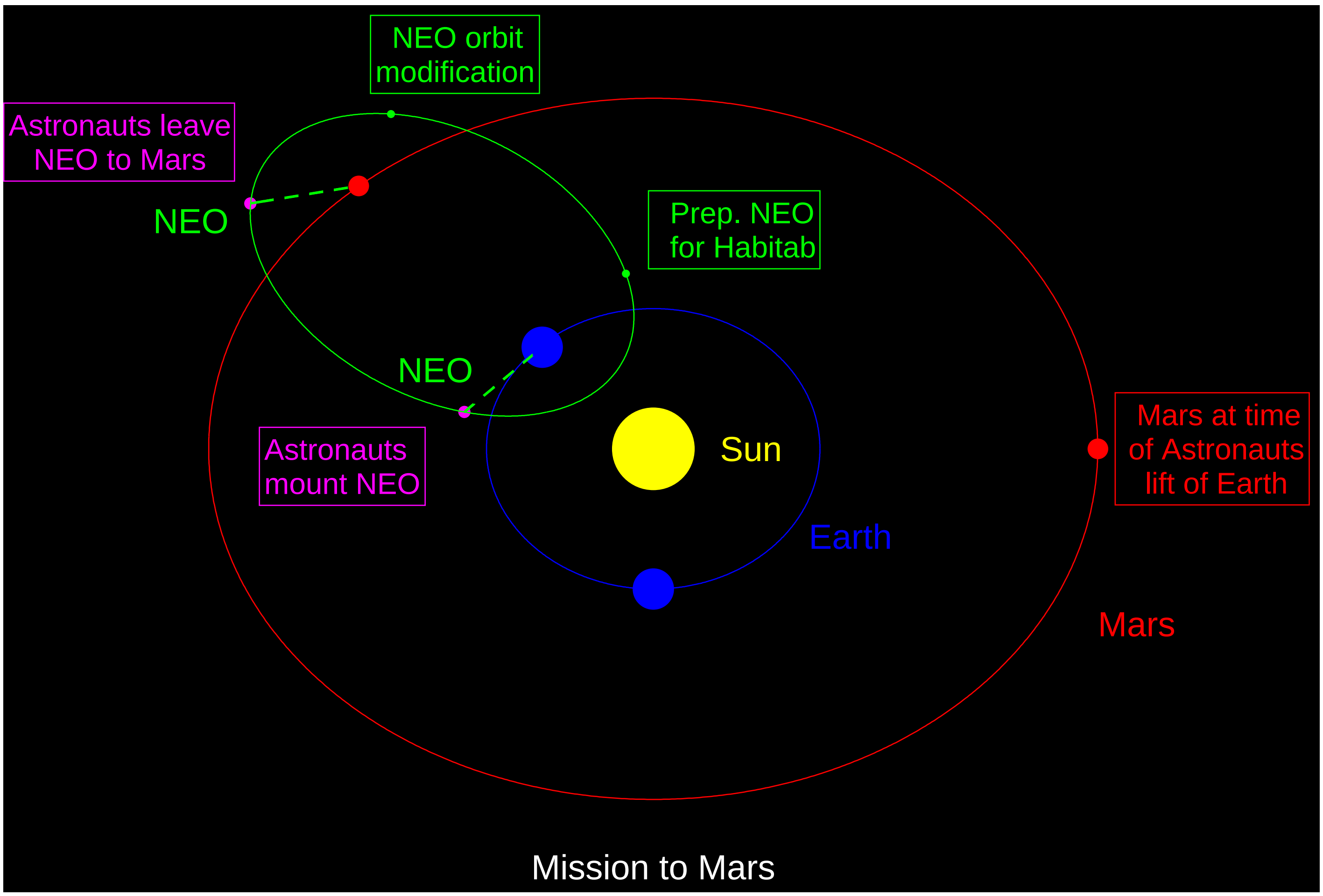
NOTE: Due to a lack of information on the physical properties of the asteroids listed in this table, only their orbital parameters are included. Information from the NASA JPL Small Body Database and the IAU Minor Planet Center.

Asteroid Name	NEA Group	Aphelion (AU)	Perihelion (AU)	Semi-Major Axis (AU)	Eccentricity	Orbital Period (Days)	Ecliptic Inclination (°)
(2008 DG5)	Apollo	1.5605	0.9511	1.2558	0.2426	513.6417	-4.7669
(2005 ER70)	Apollo	1.4977	0.9516	1.2246	0.2230	494.6646	-0.3221
(2010 JT39)	Apollo	1.4533	0.9522	1.2028	0.2083	481.4665	-2.1030
(2002 GR)	Apollo	1.4506	0.9523	1.2014	0.2074	480.6623	0.1691
(2004 WH1)	Apollo	1.4419	0.9543	1.1981	0.2035	478.6652	-4.4944
(2006 HZ5)	Apollo	1.4490	0.9544	1.2017	0.2058	480.8212	-2.8761
(2009 EK1)	Apollo	1.5271	0.9567	1.2419	0.2297	505.1501	-6.1663
(2010 MY1)	Apollo	1.4692	0.9577	1.2134	0.2108	487.8864	2.5597
(2009 TQ)	Apollo	1.5513	0.9596	1.2554	0.2357	513.4480	9.3325
(2005 TA)	Apollo	1.6010	0.9603	1.2806	0.2502	528.9844	6.0552
162173 (1999 JU3)	Apollo	1.4159	0.9632	1.1895	0.1903	473.5504	-1.2710
(2002 NV16)	Apollo	1.5099	0.9653	1.2376	0.2200	502.5209	2.2717
(2011 YT62)	Apollo	1.4315	0.9666	1.1990	0.1939	479.2262	-1.0102
(2011 MJ)	Apollo	1.4750	0.9668	1.2209	0.2081	492.3856	3.2363
(2009 XF2)	Apollo	1.6038	0.9684	1.2861	0.2470	532.3440	1.2930
(2006 HU50)	Apollo	1.6053	0.9698	1.2875	0.2468	533.2665	-4.9307
162162 (1999 DB7)	Apollo	1.4408	0.9709	1.2058	0.1948	483.3248	3.6853
(2012 KA42)	Apollo	1.6290	0.9727	1.3009	0.2522	541.5547	4.1647
(2001 AV43)	Apollo	1.5811	0.9730	1.2771	0.2381	526.7653	9.1753
(2009 XP2)	Apollo	1.4517	0.9732	1.2125	0.1973	487.3171	2.0990
(2009 XZ6)	Apollo	1.4681	0.9754	1.2218	0.2016	492.9218	-0.6844
(2008 AF3)	Apollo	1.4377	0.9759	1.2068	0.1913	483.9206	-5.0828
(2006 BP147)	Apollo	1.5964	0.9777	1.2871	0.2403	532.9818	-2.1832
(2009 YS)	Apollo	1.4063	0.9784	1.1924	0.1794	475.2350	-0.4020
(2010 KE)	Apollo	1.6159	0.9792	1.2975	0.2454	539.4822	-1.1647

Asteroid Name	NEA Group	Aphelion (AU)	Perihelion (AU)	Semi-Major Axis (AU)	Eccentricity	Orbital Period (Days)	Ecliptic Inclination (°)
(2002 FB)	Apollo	1.4308	0.9804	1.2056	0.1868	483.1919	-0.1092
164222 (2004 RN9)	Apollo	1.6271	0.9821	1.3046	0.2472	543.8815	3.2343
(2012 HC25)	Apollo	1.4381	0.9822	1.2101	0.1884	485.8995	-0.7454
(2011 HF)	Apollo	1.5842	0.9823	1.2832	0.2346	530.5952	-5.5246
(2003 QH5)	Apollo	1.5382	0.9824	1.2603	0.2205	516.4310	-0.0560
(2003 YS70)	Apollo	1.5922	0.9828	1.2875	0.2367	533.2459	7.1045
(2011 PU1)	Apollo	1.6347	0.9838	1.3092	0.2486	546.7916	-4.2856
(2010 PR10)	Apollo	1.4094	0.9873	1.1984	0.1761	478.8338	2.0077
(2005 YA37)	Apollo	1.5718	0.9884	1.2801	0.2279	528.6219	-5.2472
(2009 QE34)	Apollo	1.5882	0.9904	1.2893	0.2319	534.3524	5.3295
(2009 FQ32)	Apollo	1.4566	0.9941	1.2253	0.1887	495.0843	-1.0081
(2008 CE119)	Apollo	1.4246	0.9956	1.2101	0.1773	485.8956	0.5736
(2003 BS35)	Apollo	1.5155	0.9957	1.2556	0.2070	513.5420	2.4828
(2010 XO)	Apollo	1.6280	0.9958	1.3119	0.2409	548.4778	-6.0668
(2012 FN)	Apollo	1.4253	0.9961	1.2107	0.1772	486.2437	-4.0468
(2007 TG71)	Apollo	1.6063	0.9974	1.3019	0.2339	542.1843	8.4795
(2003 GD42)	Apollo	1.5907	0.9984	1.2945	0.2288	537.6056	-0.8471
(2006 HW50)	Apollo	1.4712	0.9998	1.2355	0.1907	501.2581	-1.6122
(2008 XS)	Apollo	1.5518	1.0025	1.2771	0.2150	526.8097	-6.4801
(2011 YP10)	Apollo	1.4189	1.0029	1.2109	0.1718	486.3617	2.1725
(2008 TS10)	Apollo	1.5157	1.0034	1.2596	0.2034	515.9875	-5.5296
(2008 VA4)	Apollo	1.5673	1.0034	1.2854	0.2193	531.9096	3.1624
(2012 MY2)	Apollo	1.5173	1.0035	1.2604	0.2038	516.4728	-1.3272
(2008 UL3)	Apollo	1.5840	1.0045	1.2942	0.2239	537.4314	-2.3003
(2010 CE55)	Apollo	1.5734	1.0061	1.2897	0.2199	534.6309	0.0391
(2008 GE)	Apollo	1.5372	1.0062	1.2717	0.2088	523.4643	-6.4160
(2011 YJ6)	Apollo	1.5750	1.0065	1.2908	0.2202	535.2711	4.6928
(1993 KA)	Apollo	1.5036	1.0074	1.2555	0.1976	513.4666	8.9861
162783 (2000	Apollo	1.6170	1.0083	1.3126	0.2318	548.9364	6.5909

YJ11)							
(2012 FQ35)	Apollo	1.5721	1.0090	1.2906	0.2181	535.1432	-0.6601
Asteroid Name	**NEA Group**	**Aphelion (AU)**	**Perihelion (AU)**	**Semi-Major Axis (AU)**	**Eccentricity**	**Orbital Period (Days)**	**Ecliptic Inclination (°)**
190491 (2000 FJ10)	Apollo	1.6276	1.0097	1.3187	0.2343	552.7099	8.9571
(2007 TE71)	Apollo	1.4771	1.0106	1.2438	0.1875	506.3500	0.2928
(2011 CY7)	Apollo	1.5633	1.0119	1.2876	0.2141	533.3156	-4.8784
(2012 WM28)	Apollo	1.4162	1.0137	1.2150	0.1656	488.8148	2.7910
(2011 AA23)	Apollo	1.5776	1.0138	1.2957	0.2176	538.3294	-3.2402
(2011 OK45)	Apollo	1.5675	1.0144	1.2909	0.2142	535.3777	8.5900
(2005 GP21)	Apollo	1.6020	1.0145	1.3082	0.2246	546.1800	-3.9861
(2005 RK3)	Apollo	1.4783	1.0163	1.2473	0.1852	508.4446	-3.4296
(2007 SO6)	Amor	1.6212	1.0184	1.3198	0.2284	553.4185	6.0501
(2009 KT4)	Amor	1.5349	1.0188	1.2769	0.2021	526.6559	3.8431
(2005 AJ3)	Amor	1.5314	1.0189	1.2752	0.2010	525.5853	0.3912
(2010 RM122)	Amor	1.5868	1.0197	1.3033	0.2176	543.0588	0.0390
(2005 GN22)	Amor	1.5486	1.0204	1.2845	0.2056	531.3828	-4.9569
(2005 PA5)	Amor	1.6215	1.0217	1.3216	0.2269	554.5685	8.1751
(2012 CA53)	Amor	1.5086	1.0220	1.2653	0.1923	519.5048	3.6413
(2010 RA12)	Amor	1.6321	1.0228	1.3275	0.2295	558.2582	5.8362
(2011 LV10)	Amor	1.6346	1.0235	1.3290	0.2299	559.2583	2.4680
(2011 TP6)	Amor	1.6160	1.0240	1.3200	0.2242	553.5541	-4.5679
2006 KQ1	Amor	1.4626	1.0262	1.2444	0.1754	507.0319	2.4484
(2007 VW7)	Amor	1.6311	1.0268	1.3290	0.2274	559.2133	5.2953
(2011 HH)	Amor	1.5838	1.0271	1.3055	0.2132	544.4420	-3.6791
(2004 LX5)	Amor	1.5859	1.0278	1.3068	0.2135	545.3018	6.4368
2005 OH3	Amor	1.4446	1.0287	1.2367	0.1681	502.3150	-2.3640
(2009 TB3)	Amor	1.6085	1.0296	1.3190	0.2195	552.9422	5.0692
67367 (2000 LY27)	Amor	1.5869	1.0302	1.3085	0.2127	546.3660	1.8687
(2011 PT)	Amor	1.5936	1.0307	1.3121	0.2145	548.6251	-4.9582

Asteroid Name	NEA Group	Aphelion (AU)	Perihelion (AU)	Semi-Major Axis (AU)	Eccentricity	Orbital Period (Days)	Ecliptic Inclination (°)
(2005 EZ169)	Amor	1.5995	1.0334	1.3164	0.2150	551.3120	-4.4120
(2011 FQ29)	Amor	1.6262	1.0334	1.3298	0.2229	559.7525	-3.6271
(2003 GA)	Amor	1.5267	1.0365	1.2816	0.1912	529.5716	-3.3133
2012 DK61	Amor	1.4494	1.0374	1.2434	0.1657	506.4123	-0.8882
(2000 TE2)	Amor	1.6030	1.0380	1.3205	0.2139	553.8814	-0.9357
(2011 UJ169)	Amor	1.6180	1.0386	1.3283	0.2181	558.7696	3.3722
2009 SC15	Amor	1.4907	1.0387	1.2647	0.1787	519.4736	-0.3144
2007 YJ1	Amor	1.4890	1.0393	1.2641	0.1779	519.1493	-3.1464
(2012 LW7)	Amor	1.6218	1.0404	1.3311	0.2184	560.5605	1.4825
(2005 JB46)	Amor	1.6260	1.0424	1.3342	0.2187	562.5248	6.8972
(2011 UZ275)	Amor	1.5287	1.0457	1.2872	0.1876	533.0479	1.3581
2001 KW18	Amor	1.4388	1.0464	1.2426	0.1579	505.9429	0.0655
(2008 NX)	Amor	1.5935	1.0465	1.3200	0.2072	553.5572	-6.5568


NEO orbit modification
Astronauts leave NEO to Mars
NEO
Prep. NEO for Habitab
NEO
Sun
Astronauts mount NEO
Mars at time of Astronauts lift of Earth
Earth
Mars
Mission to Mars