3 MONTHS TRANSIT TIME TO MARS FOR HUMAN MISSIONS USING SPACEX STARSHIP

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ABSTRACT

Historically, spacecraft have followed trajectories that took between six and nine months to reach Mars, using traditional chemical propulsion on roughly Hohmann transfers. It is commonly believed that advances in propulsion technology, such as nuclear thermal or VASIMR, are necessary to reduce that transit time. In this paper, we show the feasibility of transit to Mars using the SpaceX Starship taking 90 days, with existing technology proven in 2024. We outline two trajectories that reduce each transit to between 90 and 104 days each way. These trajectories are within NASA career radiation limits, while 180-day trajectories are not.

1 Introduction

A key challenge for human missions to Mars is the lengthy transit time (6–9 months[1, 2]) using chemical or nuclear thermal rockets and low-energy trajectories. Such durations not only complicate mission design and technology requirements, but also raise questions about crew survivability and overall success. Studies[3, 4] regularly emphasize how time in interplanetary space increases mission risks in multiple ways: crew health, radiation, resupply logistics, and psychological factors. Thus, shorter Mars transit times have become a major focus of new propulsion developments[5] and programmatic objectives outlined in NASA papers[6]. We show that significantly faster transits, of 90 days, can be achieved with existing chemical rocketry technology without need for large-scale space nuclear power or new propulsion technology.

2 Mission outline

As outlined in the SpaceX Starship Mars plan[7] the crew mission would involve four cargo Starships and two crew Starships. The crew Starships would require 15 refuels in low Earth orbit (LEO) assuming Block 2 Starship is capable of 100t (metric tonnes) to LEO[8] and has 1500t propellant capacity. The cargo ships would be sent on longer low-energy trajectories, each requiring four refuels in LEO. The outlined mission involves $\sim$40 launches of Starship Superheavy[Fig1] which given a speculative cadence of 1000[9] launches per year would be achievable in 2-3 weeks. If SpaceX is unable to improve launch rate beyond their current Falcon 9 cadence (15 launches/month as demonstrated in November 2024) these launches would take 2-3 months. Upon arrival at Mars, 1500t of propellant per ship would be produced from local carbon dioxide and water ice using electrolyzers and a Sabatier ISRU (in situ-resource-utilization) reactor[7][10]. Astronauts would explore the local area and perform science experiments. When near the return window, one crew and 3-4 cargo ships would be refuelled. All ships would launch into LMO (low Mars orbit) where the cargo ships would transfer the majority of their propellant to the crew ship until it is fully refueled. The cargo ships would then return to the surface of Mars, while the crew ship would head for Earth. This could be repeated for the other crew ship.

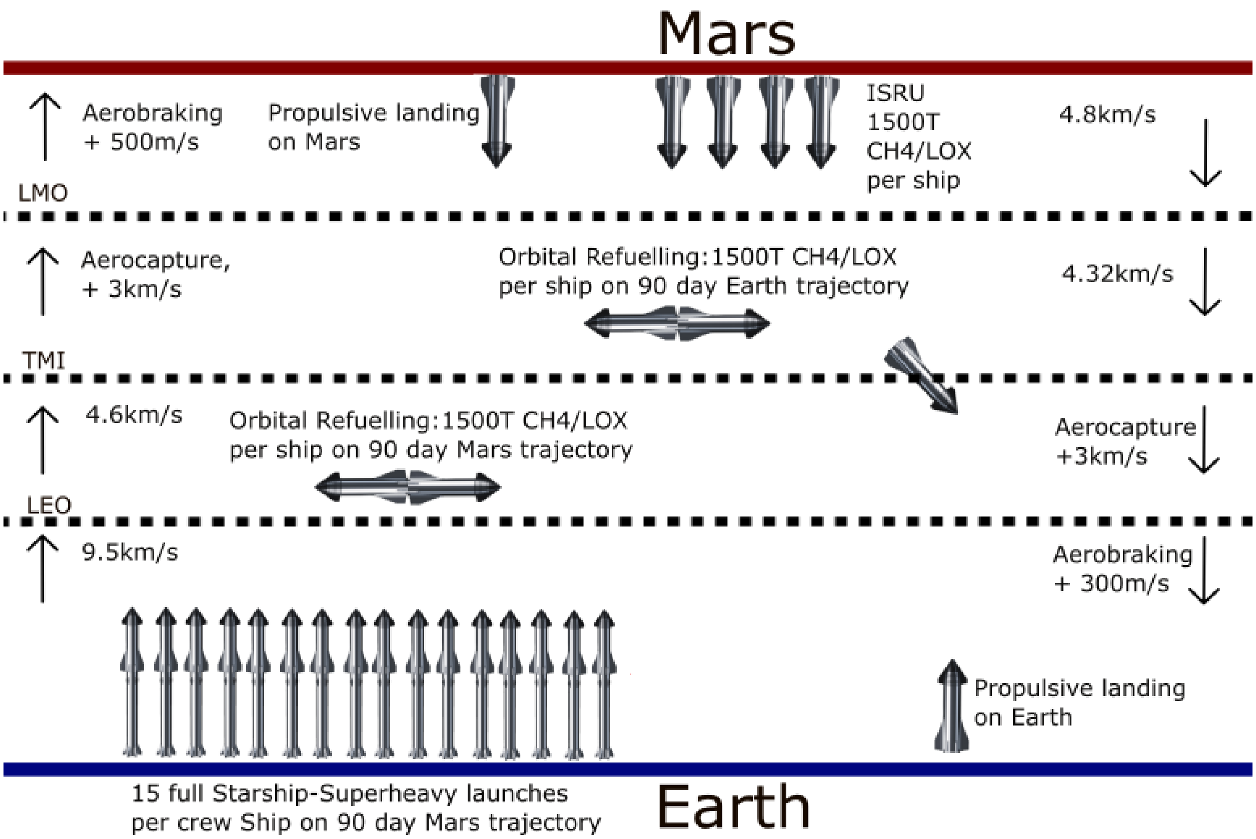

Figure 1: Starship 2033 mission with 90-day transit architecture. The DV cost of each step is labeled next to the arrows.

3 Trajectory

3.1 Assumptions

We took the dry mass of an empty tanker Starship to be 100t[11] and the mass of a crew habitat to be 63t (see Appendix A). We took the tanks to have 1500t of propellant capacity, of which 1170t is LOX (liquid Oxygen) and 330t is LCH4(liquid Methane)[8]. The trajectories were calculated with patched conics 2-body approximations using the poliastro python library[12][13]. As is standard in preliminary Mars mission architecture studies[1], we employ Lambert-arc solutions for Earth–Mars transfers, effectively treating the spacecraft's heliocentric leg as a two-body problem (Sun + vehicle), and each hyperbolic planet exit/entry as a two-body problem (Earth/Mars + vehicle). Higher-order multi-body perturbations are negligible for initial DV (delta-velocity) estimates and remain consistent with the approach used historically by NASA. We iterated the poliastro Lambert-arc solver over 1-day timesteps in the 2030s to look for the lowest ejection DV solutions in the Sun reference frame. We then calculated the C3 (characteristic energy) of said trajectory when propagated to edge of Mars/Earths sphere of influence. Then a hyperbolic trajectory with that C3 could be calculated, and thus the ejection/arrival DVs could be calculated. A porkchop plot of trajectories in the 2030s is shown[fig4].

4 Earth to Mars

We outline two 90-day Earth to Mars transit opportunities in the mid 2030s.

- 2033 trajectory: Ejection from Earth on 2033-04-30 with ~4.6km/s from a 150km circular LEO. Mars aerocapture ~ 90 days later[fig 2].

- 2035 trajectory: Ejection on 2035-07-15, also ∼4.6km/s from LEO, with aerocapture at Mars ∼90 days later[fig 3].

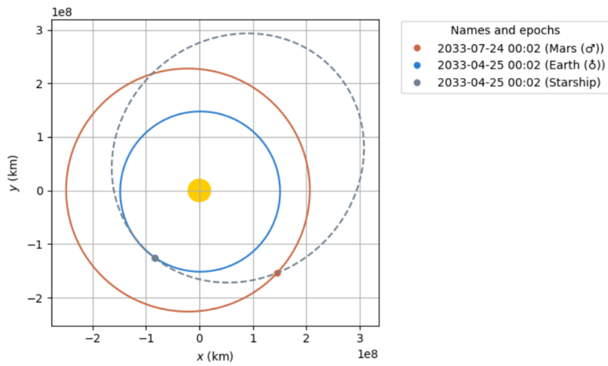

Figure 2: 2033 90 day transit

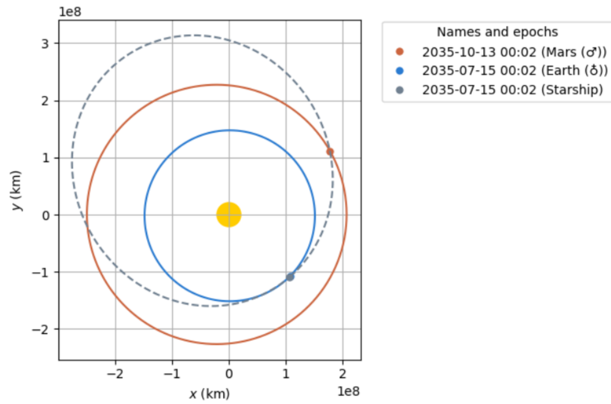

Figure 3: 2035 90 day transit

The respective characteristic energies (C_3) for each trajectory are roughly $31.5km^2/s^2$ and $32km^2/s^2$. There are no trajectories with similarly low ejection DV until 2048-04-08 with 4.60 km/s. Each trajectory leaves the Starship with $\sim$ 3.5km/s of DV, of which 0.5km/s[14][Appendix B] is used for the landing burn and the other 3km/s is used for a deceleration burn near Mars entry to reduce aeroloads during aerocapture[fig5]. For the both trajectories, we assume a deceleration burn 400 seconds prior to periapsis, of which $\sim 200m/s$ is lost to non-optimal oberth effect. For instance, on the 2035 trajectory, the arrival speed without a deceleration burn would be 9.73km/s, but is 6.87km/s with it. This leaves 1.85km/s to be shaved off by Mars aerocapture.

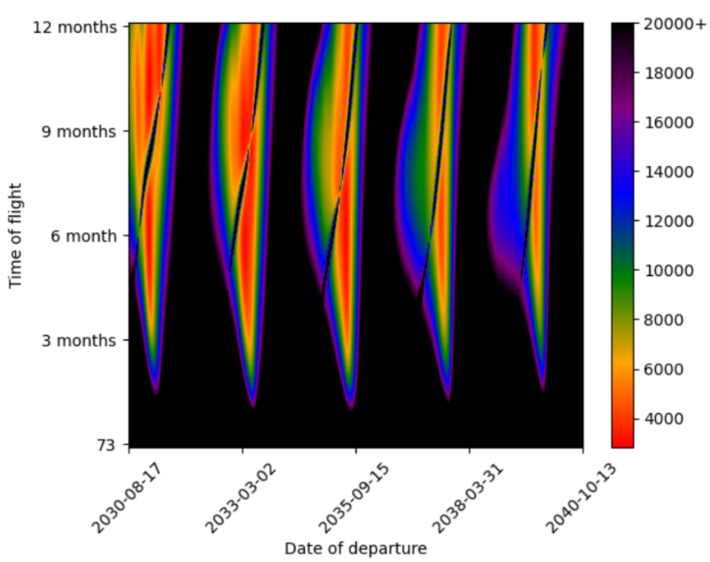

Figure 4: Earth to Mars Porkchop plot for the 2030s.

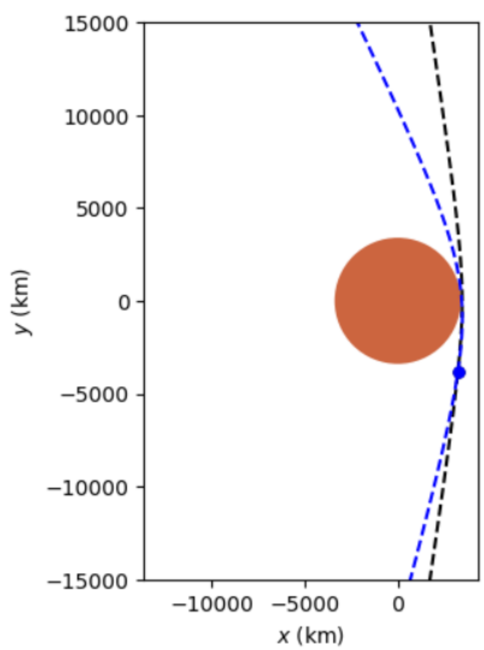

Figure 5: Arrival at Mars on 2035-10-13. The blue dotted hyperbola is trajectory after deceleration burn, and the blue dot is where the deceleration burn takes place.

4.1 Mars to Earth

Upon launch from Mars, the crew Starship enters LMO and is refueled by the empty cargo Starships also fuelled by ISRU on the surface of Mars. Each tanker flight may deliver approximately 300 t of propellant if the Mars ascent DV is about 4,800m/s[15]. Approximately 4–5 flights will be needed for full refueling. We identify only one suitable 90-day return in 2035—on 2035-07-02, requiring a DV of about 4.32 km/s for ejection from LMO. Summer/Autumn 2037 offers a 90-day route (2037-08-31, requiring $\sim$ 5.87 km/s) but yields a dangerously high Earth arrival velocity ($\sim$ 14.1 km/s at periapsis). Instead, we recommend a 104-day trip starting 2037-08-23, arriving at Earth on 2037-12-05 at a periapsis velocity of about 11.86 km/s—closer to typical lunar[16] or Hohmann-like reentry energies and presumably within Starship's aerodynamic/thermal design limits[17].

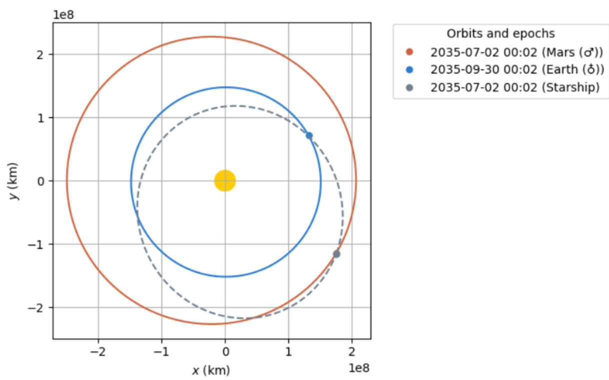

Figure 6: 2035 90 day return

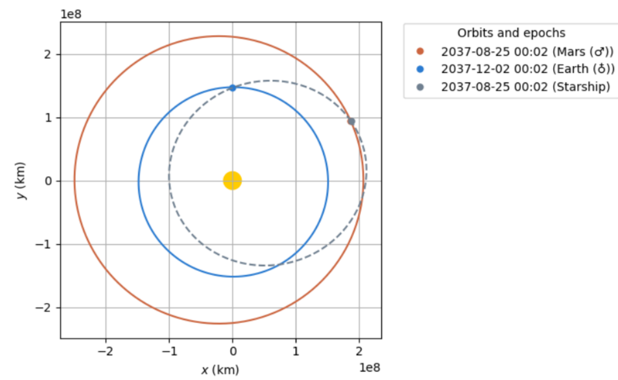

Figure 7: 2037 104 day return

4.2 Boiloff

The cryogenic LOX & LCH4 propellant stored in the main tanks of the Starship used in the deceleration burns must survive the 90-day transit. Starship Human landing system (HLS) is contracted to land the next humans on the Moon (by NASA) and requires 100-day loiter time in cislunar near rectilinear halo orbit. The vehicle, with modifications, can store cryogenic propellant for extended periods of time in deep space. The HLS modifications preclude atmospheric entry, thus we calculate the expected thermal properties without these modifications on Block 2 Starship. The thermally optimal attitude is where the Starship points directly at the Sun to both reduce the area absorbing solar radiation, and to insulate the main tanks with the crew cabin. Any propellant in the header tanks could be moved to the main tanks during cruise and moved back for landing[18].

Both tanks will nominally be pressurized to 6 bar[20] where methane has a boiling point of 140K[21] and oxygen at 113K[22]. The methane tank externally is composed of three 1.83m tall, 9m diameter steel rings[23][Fig8]. The oxygen tank is composed of six of these rings thus has twice the area. Half of each tank is bare 304X stainless steel, and the other half is that steel covered with proprietary ceramic thermal protection tiles. As these are proprietary SpaceX materials, we do not know their exact specifications, but they are similar to/derivatives of 304L stainless steel and the NASA LI-900 Space Shuttle TPS material respectively and thus have very similar emissivities. The emissivity of both vary with flight wear and other parameters, but we take them to be 0.4[24] and 0.8[25] respectively. The average emissivity $\bar{\epsilon}$ of the Starship tank section is thus 0.6. We take the area of the methane tank to be A_m, the area of the oxygen tank to be A_o, the respective temperatures to be T_a and T_o and the Stefan-Boltzmann constant to be σ. By the Stefan-Boltzmann law the radiated power from the tanks each at saturation temperature is:

$$P_r = \bar{\epsilon}\sigma(A_m T_m^4 + A_o T_o^4) = 0.6\sigma(310 * (140^4) + 620 * (113^4))m^2 K^4 = 9836W$$

If the methane tank is in thermal equilibrium with the oxygen tank, then the radiated power is:

$$P_r = \bar{\epsilon}\sigma T_o^4 (A_m + A_o) = 0.6\sigma * 113^4 * (310 + 620)m^2 K^4 = 5166W$$

The crew cabin is assumed to be at a human friendly 290K temperature, and assuming the bottom plate facing the propellant tanks is a polished aluminium sheet of emissivity of 0.06, the emitted power is:

$$P = 0.06 * \sigma * 290^4 * (\pi * 4.5^2)m^2 K^4 = 1530W$$

into the methane tank. Conduction through the steel skin is negligible: the conductivity of stainless steel is $\sim 15WK^{-1}m^{-1}$[26] at 300K, and decreases with temperature. There is a $\sim 200K$ temperature drop from the crew cabin

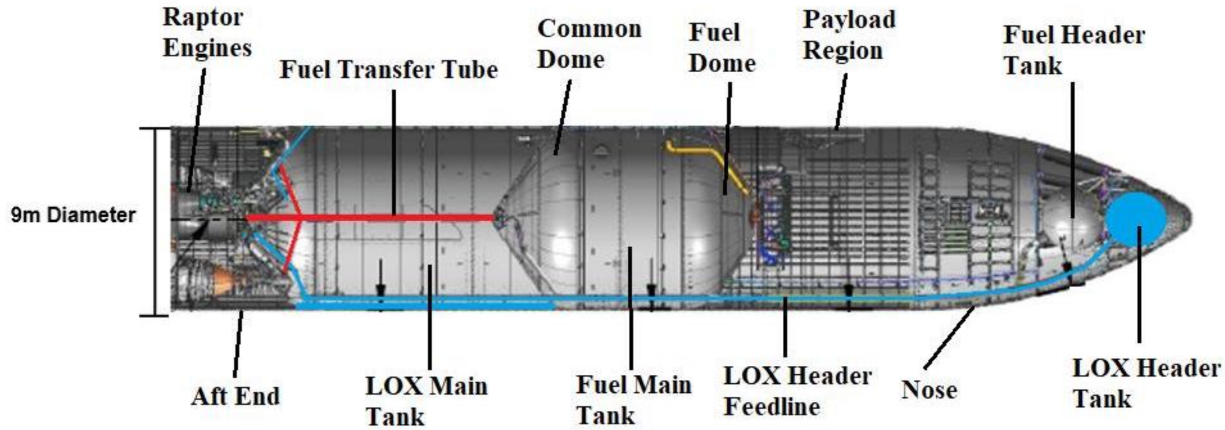

Figure 8: Starship internal diagram[19]. The astronaut habitat will be placed in the payload region.

outer steel to the tank outer steel, which we can assume takes place over the distance of one ring segment. The steel is 9m diameter and 4mm thick[27], thus the conducted power is $\sim 400W$, which is small compared to the radiated heat. As the sun is only hitting the nose cone, solar radiation management is only a problem for the crew cabin. Thus the tanks will radiate more power out ($5KW - 10KW$) than they receive ($\sim 2KW$) and the cryogenic propellant will not boil off in the 90-day transit to Mars. These calculations obviously ignore radiation from sources other than the Sun. Radiation from interstellar sources is negligible, but Earth/Mars-shine along with planetary black-body emissions is nominally not negligible and contributes significantly to the engineering challenges of long-duration LEO cryogenic storage. We ignore it as the Starship spends very little time near Earth or Mars (except when the tanks are intended to be empty, or being actively filled).

4.3 Estimated radiation dosage

The majority of radiation dosage in interplanetary space is GCR (galactic cosmic ray)[28], with the exception of Solar storms. Modern human deep space craft employ solar storm shelters[29], and Starship will also, thus the radiation exposure from Solar events will be mitigated. The main focus is on GCR, which cannot be easily shielded. The GCR dosage in interplanetary space has been measured at $1.84 \pm 0.33mSv$ per day[28] which does not significantly change with distance to the Sun during a Mars mission. Thus the radiation dosage for a 90-day transit is halved from a 180-day transit. Assuming significant shielding on the surface of Mars (which can be provided by local materials such as ice and Mars dirt), the radiation during transit will be the majority of the total mission radiation. This is $331 \pm 54mSv$. Taking the 104-day return trajectory in 2037 will lead to the total dose increasing to $357 \pm 58mSv$. This is below the allowed career radiation dose for astronauts[30] - 1000mSv and 600mSv for 35-year-old men and women respectively.

5 Reentry simulations

Both trajectories involve significant aerocapture maneuvers where the Starship enters the upper atmosphere of Earth or Mars and uses atmospheric drag to decelerate from a hyperbolic trajectory that moves faster than the respective planet's escape velocity to an elliptical captured orbit [Fig 9]. Because hyperbolic trajectories around planets have a lower curvature than captured orbits, the amount of time spent in the atmosphere is not long, so the necessary acceleration to capture is high. We performed an approximate simulation of the Starship hyperbolic atmospheric entry for the 2037 Earth return trajectory (the highest energy aerocapture among our papers four proposed aerocapture maneuvers), assuming a lift to drag ratio of 0.5[31], and an inverted $70°$ entry angle allowing for negative lift to bend the trajectory downwards. We used a Cowell propagator and the estimated Starship lift and drag coefficients[31], to get a ballpark figure on maximum deceleration experienced during the maneuver. We estimate the maximum deceleration[Fig10] to be approximately 2g, which is significantly less than is commonly experienced by astronauts during reentry[32]. Thus we think these given aerocapture maneuvers should be within survivable ranges for human missions.

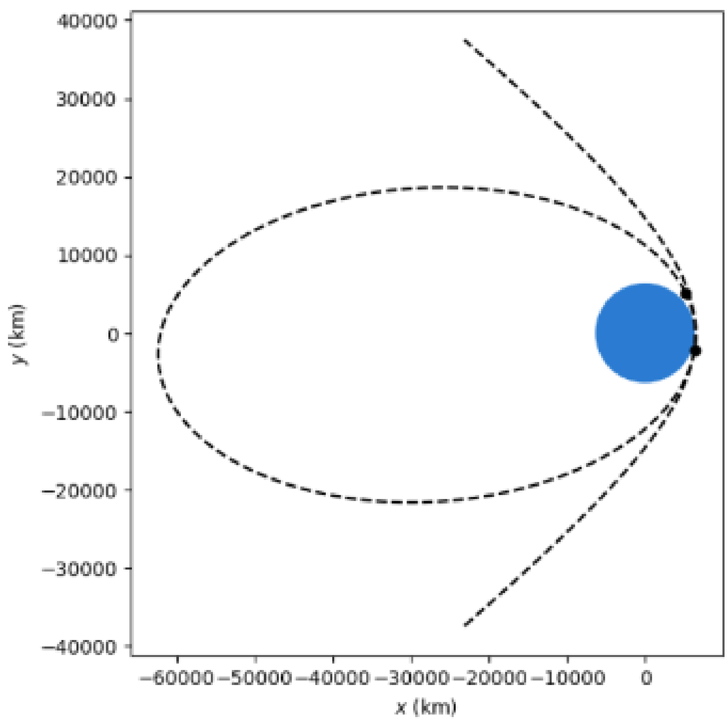

Figure 9: Orbits of 2037 arrival at Earth before and after aerocapture

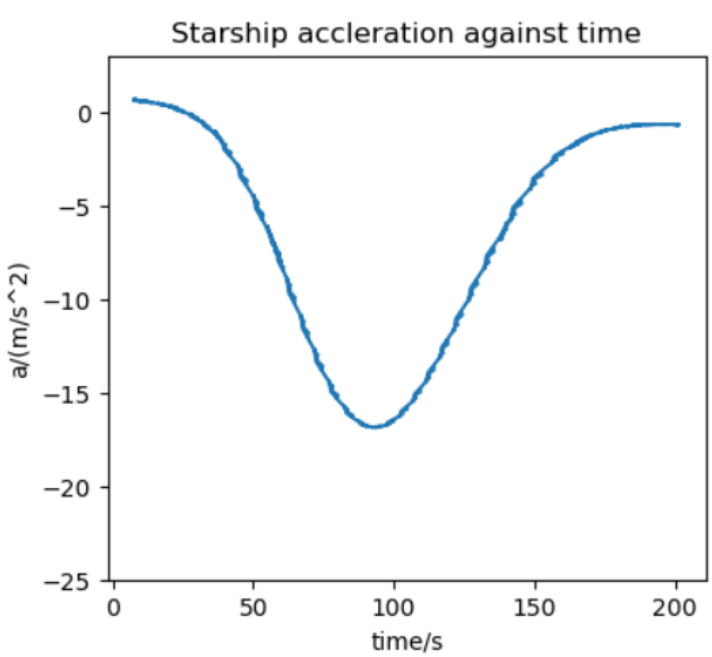

Figure 10: Starship acceleration during the 2037 aerocapture

6 Conclusion

This paper demonstrates that a 90-day transit to Mars (and correspondingly shorter return trips) is feasible using existing chemical rocket technology—specifically, the SpaceX Starship architecture. By employing higher-energy transfers (compared to traditional Hohmann windows) and aerocapture at Mars, we achieve Earth departure DV near 4.6km/s and a total 90-day in-transit time. The resulting radiation dose is effectively halved compared with 6–9 month baseline trajectories, and cryogenic propellant boil-off appears manageable given Starship's design and orientation.

While we emphasize that this approach requires a high launch cadence for refueling Starship in LEO and robust aerocapture thermal protection, neither aspect represents fundamentally untested physics - only an operational scaling of existing flight-proven elements. If Starship meets its projected performance and if in-orbit refueling proceeds on a large scale, then 3-month human journeys to Mars (with significantly reduced exposure to deep-space hazards) become a real possibility.

7 Appendix-A: Crew habitat mass estimates

The design of a crew habitat necessary to keep astronauts alive during this 90 day transit has not been revealed by SpaceX so it is necessary to estimate this. Skylab is the most relevant historical spacecraft as it involved adding a habitat to an existing rocket stage, similar to what will have to be done with Starship. Skylab took an S-IVB Saturn third stage which weighed 13t and added habitats that kept three astronauts alive without resupply for up to 84 days[33] pushing the mass to 76t. Thus we can estimate a similar habitat for Starship might weigh 63t. Though Skylab was designed only for LEO, modern materials and electronics might offset additional deep-space requirements.

We note that a team at the DLR German Aerospace Center[15] did attempt to estimate the dry mass of a crew Starship, and estimated it at 204t. They calculate the structural mass of steel in Starship to be 40t, and then calculate the mass of the propellant tanks to be 20t, assuming they are spherical tanks inside the Starship structure, adding that to the structural mass. Starship does not have spherical tanks, and instead the steel outer structure is the outside of the tank[19][Fig8], so this paper 'double counts' the mass of the propellant tanks. The paper assumes cold gas helium is used for Starship's RCS (Reaction Control System), but in reality it uses hot gas from the main tanks[34]. They add an extra 5.5t for this hypothetical helium RCS and the supporting tanks. The paper claims Starship uses PICA-X as its thermal protection system, which was in the design from 2016-2019, but was changed to ceramic tiles in 2019[35]. The paper uses the mass of Raptor 1 engines which are 2t. Raptor 1 last flew in 2021, and the under testing Raptor 3 engines weigh 1.5t[36], reducing the mass for a 9-engine Starship by 4.5t. They then add a 20% mass margin. These stated reasons are why we think that a crew Starship could mass significantly less than their estimate.

8 Appendix B: Landing burn DV

The 500m/s landing burn DV estimate is from Elon Musk's 2017 IAC presentation[14] where he claims Mars reentry bleeds 99% of the orbital energy off. This is 90% of the orbital velocity, thus we think 500m/s is a reasonable estimate for landing burn DV. These values are for the 2017 BFS design, which is similar size and shape to the 2024 Starship design, thus will have similar terminal velocity and landing burn DV.

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