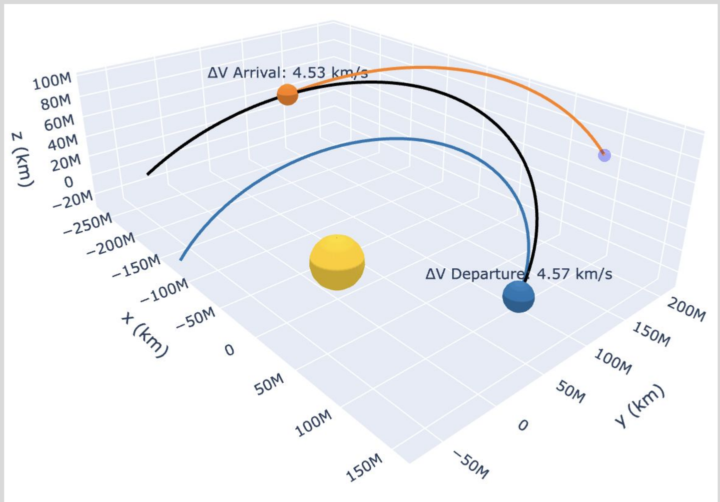
Pitzer College | Department of Natural Sciences | Physics

The Requirements of Nuclear Propulsion for Human Mars Exploration

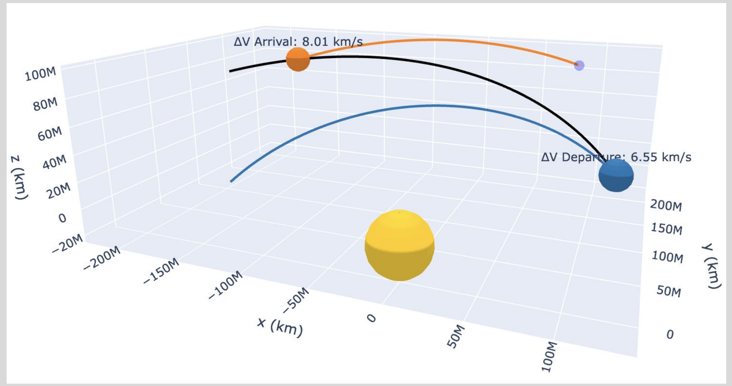
By Scotia Rollins

Sample Trajectory Plots:



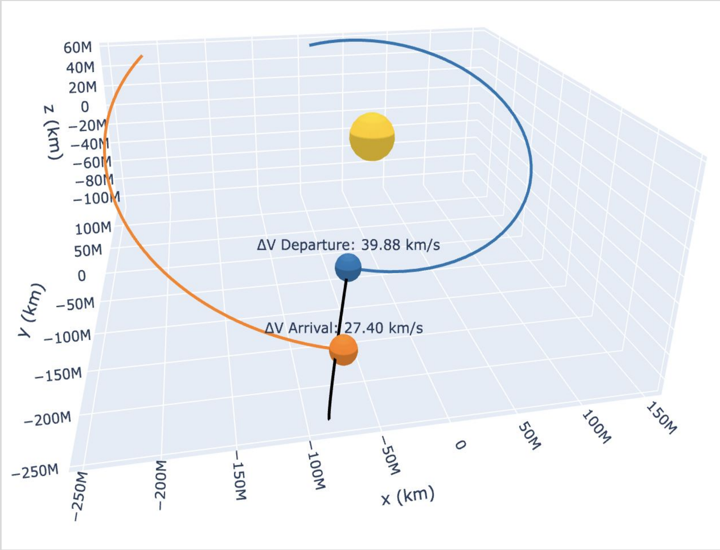
Conjunction-Class Optimal Trajectory Option:

- *ΔV: 9.09 km/s*
- *190-day transit*
- *Blue circle in Fig. 2*



Opposition-Class Optimal Trajectory Option:

- *ΔV: 14.55 km/s*
- *130-day transit*
- *Red circle in Fig. 2*



Inefficient Hyperbolic Trajectory Example:

- *ΔV: 67.28 km/s*
- *220-day transit*

Abstract

This thesis examines propulsion requirements for a crewed Mars mission, focusing on how mission architecture, specifically opposition- vs. conjunction-class trajectories, influences the choice between nuclear thermal (NTP) and nuclear electric propulsion (NEP). Using the Tsiolkovsky rocket equation, it is shown that chemical propulsion is insufficient for interplanetary ΔV demands, motivating nuclear alternatives. An engineering comparison of NTP and NEP systems evaluates thrust, specific impulse, system mass, and power-to-mass ratios. NTP offers high thrust but lower efficiency, favoring short transits; NEP provides higher efficiency and is suited to long-duration missions. Trajectory modeling in Python, using *poliastro* and JPL ephemerides, identifies optimal launch windows and trajectories and quantifies their respective propulsion needs. Results show that while NEP may be effective for either conjunction- or opposition-class missions, NTP may only be feasible for the latter. These findings emphasize the importance of integrating propulsion choices with mission architecture early in planning. With a 2039 launch opportunity approaching, strategic investment in nuclear propulsion is essential for sustainable human Mars exploration.

Crewed Mars missions, motivated by science and exploration objectives that require human participation, involve a critical choice between nuclear thermal (NTP) and nuclear electric (NEP) propulsion. Propulsive requirements depend heavily on trajectory design: NEP is more effective long-duration conjunction-class missions, while NTP is better for short-duration opposition-class trajectories.

- **Nuclear Thermal Propulsion (NTP)**: Similar to chemical propulsion, NTP generates exhaust velocity through propellant combustion. It offers **high thrust** (F) but lower specific impulse (Isp), making it suitable for shorter transit durations characteristic of **opposition-class** missions.
- **Nuclear Electric Propulsion (NEP)**: Uses electric power to accelerate ionized gas to generate thrust. NEP has **high specific impulse** (Isp) but **low continuous thrust** (F), making it suitable for **opposition-class** or **conjunction-class** missions, which have greater overall propulsive requirements. The system is an aggregate of multiple individual thrusters.
- **Tsiolkovsky Rocket Equation**: Describes the relationship between Delta-V, specific impulse, thrust, and mass ratio. Used to calculate specific impulse requirements for optimized mission trajectories.

Launch Window Identification (Ch.4)

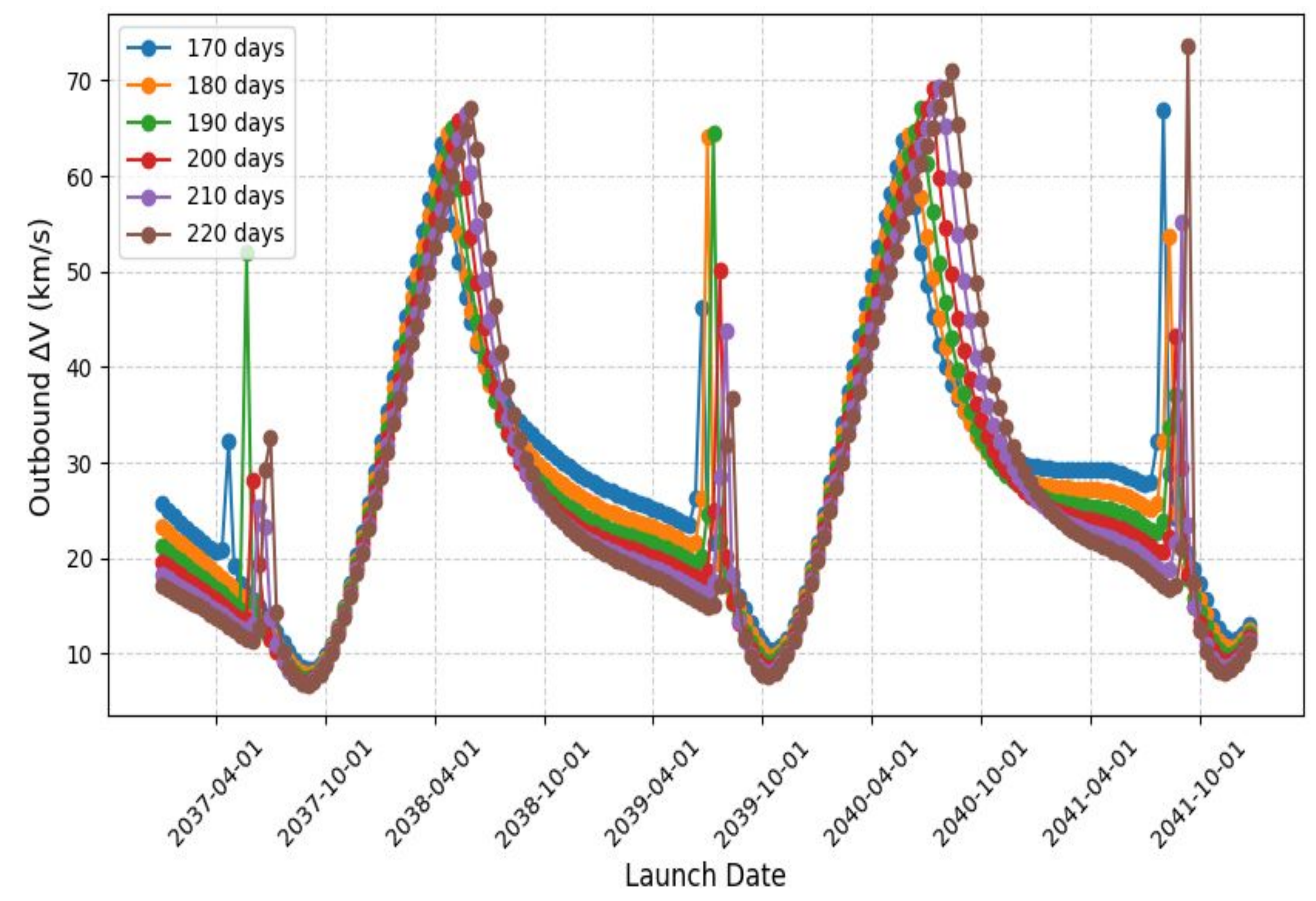


Fig. 1: Launch Date vs. Outbound *Delta-V* for 6 Transit Durations

Plot showing the time variation in total outbound ΔV for six different transit durations, used to identify optimal launch opportunities (ΔV troughs) between 2037 and 2042. Data were generated in Python using the poliastro library, which accesses planetary ephemerides from NASA JPL databases.

Theoretical Background (Ch. 2)

$$\Delta V = I_{sp} \cdot g \cdot ln(\frac{M_0}{M_f})$$

$$F_{NTP} = I_{sp} \cdot g_0 \cdot \dot{m}$$

$$F_{NEP} = \frac{2 \cdot P \cdot \eta}{I_{sp} \cdot g_0}$$

Optimization Tradeoff Between Transit Duration and ΔV (Ch. 4)

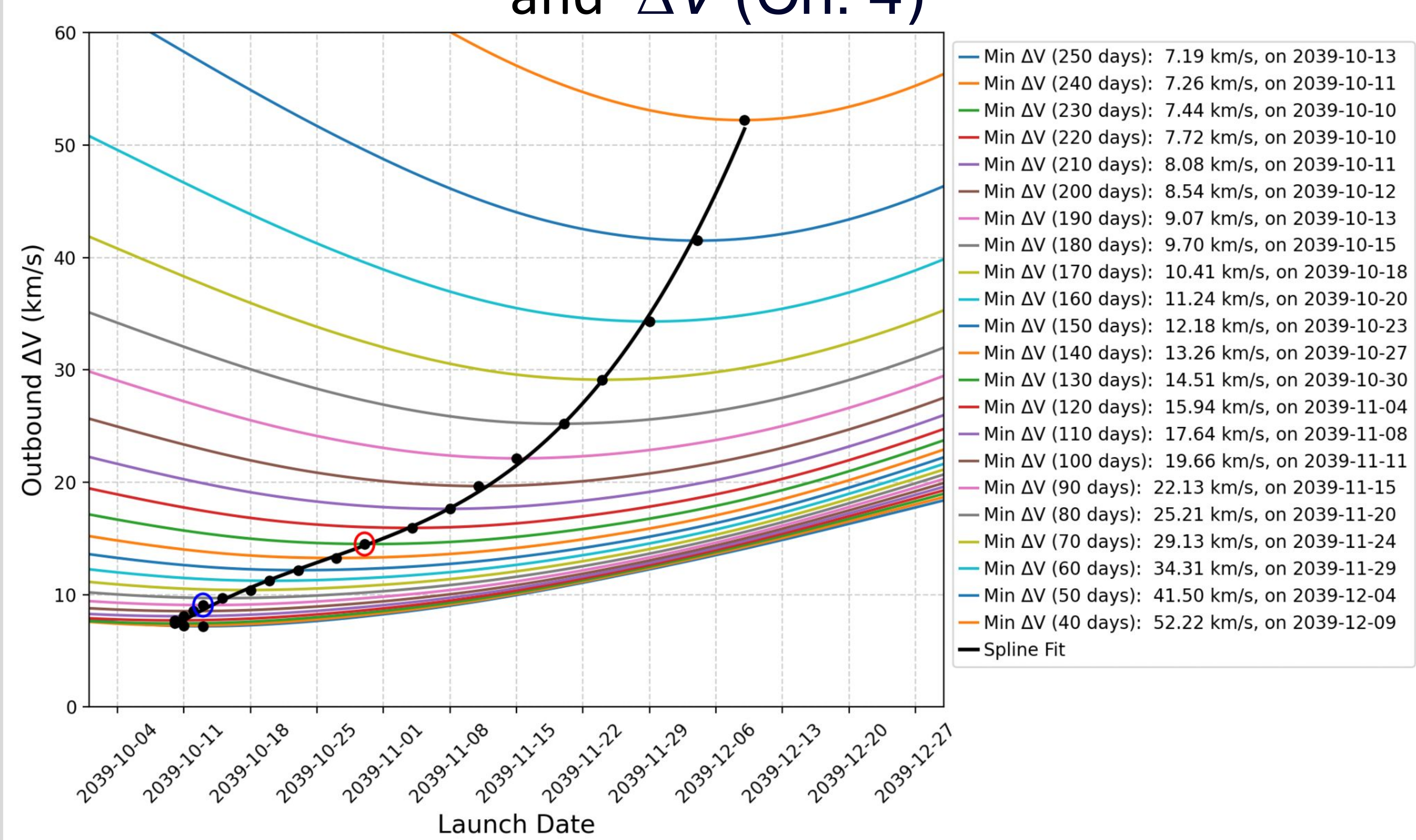


Fig 2: Launch Date vs. Minimum Outbound *Delta-V* for 2039 Launch Opportunity

Plot showing how minimum Delta-V increases with transit duration increases (represented by contours) in the launch window identified in Fig. 1 in autumn 2039. The nonlinear, piecewise-polynomial relationship reveals an optimization tradeoff between Delta-V, transit duration, and launch date. This plot was used to identify optimal conjunction- and opposition-class trajectories for further analysis (circled in blue and red–see the trajectory plots on the right).

Engineering Comparison Table (Ch.3)

Characteristic	Description	NTP	NEP
I_{sp}	Propellant efficiency (s)	~ 900 s	1800–6000 s
$\dot{m}$	Mass flow rate (kg/s)	~ 3.5	–
Power	Power available to EP thrusters	–	5.0 MWe*
F_{Earth}	Thrust on Earth (N)	$\sim 30,900$	170–560**
PMF	Propellant mass fraction	≈ 0.69	≈ 0.35
Engine Mass	Structural mass (kg)	2000–10,000	10,000–15,000
Lifetime	Total operating time	~ 4 hr	1–2 yrs

*Projected wattage requirement for baseline mission; not producible without nuclear power.
**Representative of total system thrust from multiple low-thrust electric engines; individual NEP thrusters produce only a few newtons each.

Table 3.4: Comparison of NTP and NEP propulsion characteristics (estimated)

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