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Round-Trip Mars Missions in the 2031 Window: Feasible and Extreme Scenarios Derived from CA21-Anchored Trajectories

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Abstract

This study investigates round-trip Earth–Mars–Earth missions during the 2031 opposition, applying a trajectory design framework derived from the early orbital configuration of asteroid 2001 CA21. Using Lambert-based analysis and JPL Horizons ephemerides, two optimized and dynamically consistent mission architectures were identified: a rapid scenario featuring a 33-day outbound transfer, a 30-day surface stay, and a 90-day return (total ≈ 153 days), and a feasible scenario combining a 56-day outbound transfer, a 35-day surface stay, and a 135-day return (total ≈ 226 days). Both trajectories were validated through full ephemeris computation, confirming heliocentric coherence within the CA21-anchored orbital plane and physically realistic departure and arrival velocities. The 2031 alignment minimizes plane-change penalties and yields energetically balanced outbound and inbound arcs. These findings demonstrate that short-duration, reversible Earth–Mars missions can be designed from early asteroid-derived orbital templates, establishing a predictive framework for identifying future high-velocity transfer opportunities.

Keywords: astrodynamics; rapid Mars transfer; Lambert's problem; high-energy interplanetary missions; aerocapture; nuclear-thermal propulsion; round-trip Mars mission design

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1. Introduction

(Obs: This work was developed with the support of Artificial Intelligence. The author used the ChatGPT system (OpenAI, 2025) for computational verification and text-structuring assistance, under the author's direct supervision. All physical insights, analyses, interpretations, conclusions, and theoretical innovations are attributable solely to the author.)

In recent years, the pursuit of faster interplanetary transfers has evolved from purely theoretical optimization toward data-driven trajectory synthesis. Building upon the methodology introduced in *Astrodynamics Innovation: Leveraging an Asteroid's Early Data for Faster Mars Transits* [1], the present study extends the concept of asteroid-anchored dynamics to complete round-trip Earth–Mars mission profiles within the 2031 opposition window.

The earlier work demonstrated that the initial orbital solution of the near-Earth asteroid 2001 CA21 (JPL Solution #11, 2015) could serve as a natural geometric template for ultra-fast Mars transfers. By constraining Lambert-based transfer arcs to the orbital plane of CA21, two notable Earth-to-Mars trajectories were identified: a 56-day feasible baseline, requiring $v_{\infty,\oplus} \approx 16.9\sim\mathrm{km/s}$ and $v_{\infty,\backslash mars} \approx 16.6\sim\mathrm{km/s}$, and a 33-day energetic case, geometrically valid but demanding $C_3 \approx 758\ \mathrm{km^2/s^2}$, beyond current propulsion capabilities. These results established 2031 as a benchmark alignment for both near-term and aspirational rapid-transit missions.

In this extended analysis, the framework is expanded to compute the return trajectories from Mars to Earth using the same CA21-anchored constraints and high-precision JPL Horizons ephemerides [2,3]. The results reveal two internally consistent round-trip configurations:

- The rapid scenario (33 + 30 + 90 days), departing Earth on April 20, 2031, arriving at Mars on May 23, departing Mars on June 22, and reaching Earth on September 20, 2031, for a total mission duration of ≈ 153 days. This trajectory represents a high-energy, short-way transfer pair with $v_{\infty,mars,dep} = 19.9$ km/s and $v_{\infty,\oplus,arr} = 16.8$ km/s.
- The feasible scenario (56 + 35 + 135 days), departing Earth on April 20, 2031, arriving at Mars on June 15, departing Mars on July 20, and returning to Earth on December 2, 2031, for a total duration of ≈ 226 days, with moderate energies $v_{\infty,mars,dep} = 13.6$ km/s and $v_{\infty,\oplus,arr} =$ 15.1km/s.

Both trajectories were rigorously validated through full ephemeris analysis, ensuring derivative consistency between position and velocity vectors. The shorter, high-energy mission defines the physical limit for near-term propulsion, while the longer case represents a technologically feasible baseline achievable with hybrid chemical or nuclear-thermal systems.

Together, these results establish the first closed and dynamically reversible Earth–Mars architecture derived from asteroid-based geometry. The outbound trajectories (33 and 56 days) delineate the forward energy frontier, while the return legs (90 and 135 days) confirm that the same CA21-anchored plane supports complete round-trip coherence. This dual validation — both mathematical and physical — positions 2031 as a singular benchmark for testing advanced interplanetary propulsion and mission design.

The following sections present the analytical framework, derivations, and mission-design results, establishing the 2031 window as both a feasible baseline for upcoming human or robotic Mars expeditions and an aspirational benchmark for next-generation propulsion technologies [11].

2. Analytical and Computational Framework

The determination of interplanetary trajectories in this study follows a two-phase structure: (1) the outbound leg (Earth → Mars), derived from the CA21-anchored solutions established previously; and (2) the return leg (Mars → Earth), newly computed in the same reference plane and validated against JPL Horizons ephemerides for 2031. This chapter presents the mathematical formulation, numerical implementation, and validation steps used to ensure physical consistency of both segments and the complete round-trip timelines.

2.1. Reference Frame and Initial Conditions

All calculations are in the heliocentric ecliptic J2000 frame. Planetary state vectors for Earth and Mars were obtained from the JPL Horizons system in heliocentric Cartesian form (J2000 ecliptic), sampled at 1-day intervals. The solar gravitational parameter adopted throughout was:

$$\mu_{\odot} = 1.32712440018 \times 10^{11}\ \text{km}^3\text{s}^{-2}.$$

The CA21-anchored plane is defined by the asteroid 2001 CA21 (JPL solution #11, 2015):

$$a = 1.6699\ \text{AU}, \quad e = 0.7769, \quad i = 4.97^\circ, \quad \Omega = 46.44^\circ, \quad \omega = 218.93^\circ.$$

This orientation furnishes a geometric corridor intersecting Earth's and Mars' orbits, reducing plane-change penalties and constraining high-energy transfers, using standard astrodynamics formulations [4].

2.2. Lambert Problem Formulation

Outbound and return arcs are obtained with the universal-variable Lambert method [4] connecting $\vec{r_1}$ at t_1 to $\vec{r_2}$ at t_2 for a prescribed $\Delta t = t_2 - t_1$:

$$\Delta t = \frac{1}{\sqrt{\mu_{\odot}}}\left[\chi^3 S(z) + A\sqrt{y}\right], \qquad A = \sin\Delta v\sqrt{\frac{r_1 r_2}{1-\cos\Delta v}}, \qquad (2.1)$$

$$y = r_1 + r_2 + \frac{A[zS(z)-1]}{\sqrt{C(z)}}, \quad \vec{v_1} = \frac{1}{g}(\vec{r_2} - f, \vec{r_1}), \quad \vec{v_2} = \frac{\dot{g}, \vec{r_2} - \vec{r_1}}{g}, \qquad (2.2)$$

with

$$f = 1 - \frac{y}{r_1}, \quad g = A\sqrt{\frac{y}{\mu_\odot}}, \quad \dot{g} = 1 - \frac{y}{r_2}, \tag{2.3}$$

and Stumpff functions $C(z)$and $S(z)$in their standard elliptic, parabolic, and hyperbolic forms. The Lambert solution was verified numerically [5].

In this approach, the Lambert solver operates in three dimensions, but the trajectory is constrained such that the normal vector of the transfer plane remains within $\leq 5°$ of the CA21 orbital-plane normal. This is achieved by iteratively adjusting the initial and final position vectors (r_1, r_2) through projection onto the CA21 plane until the plane offset criterion is satisfied. This ensures that both departure and arrival geometry remain consistent with the asteroid's 2015 orbital solution (JPL #11), effectively minimizing the required out-of-plane ΔV.

2.3. Computational Implementation

We used a high-precision Python implementation (tolerance 10^{-10}) and direct interpolation of Horizons vectors, $\overrightarrow{r_E}(t)$ *and* $\overrightarrow{r_M}(t)$, for sub-day accuracy. For each candidate date pair:
- departure/arrival heliocentric velocities $\overrightarrow{v_1}$ *and* $\overrightarrow{v_2}$,
- time of flight (TOF) for the leg,
- hyperbolic excess speeds at each planet:

$$v_{\infty,\oplus} = \| \overrightarrow{v_1} - \overrightarrow{v_E}(t_1) \|, \quad v_{\infty,mars} = \| \overrightarrow{v_2} - \overrightarrow{v_M}(t_2) \|, \tag{2.4}$$

and characteristic energy ($C_3 = v_{\infty,\oplus}^2$) were computed.

2.4. Validation of Ephemeris Consistency

State-vector time-derivatives (central differences, 1-day step) were compared to Horizons velocities. X and Z components match within $(< 10^{-4}\ \mathrm{kms}^{-1})$. Early Y-component mismatches traced to a draft export indexing issue were corrected; the final dataset shows full component-wise consistency across the 135-day return arc, confirming a smooth heliocentric trajectory.

2.5. Mission Profiles (Dates, Stays, and Totals)

To avoid ambiguity, we report leg durations, surface-stay duration, and total mission duration (sum of both legs plus Mars stay) with the specific dates used in this study.

Case A — Rapid Scenario (33 + 30 + 90 days)
- Earth departure: 20 Apr 2031
- Mars arrival: 23 May 2031 (33 days outbound)
- Mars surface stay: ≈ 30 days (23 May → 22 Jun 2031; aligned with the validated return window)
- Mars departure: 22 Jun 2031
- Earth arrival: 20 Sep 2031 (90 days return)
- Total mission duration (including stay): 33 + 30 + 90 = 153 days

Case B — Feasible Scenario (56 + 135 days)
- Earth departure: 20 Apr 2031
- Mars arrival: 15 Jun 2031 (56 days outbound)
- Mars surface stay: ~35 days (15 Jun → 20 Jul 2031)
- Mars departure: 20 Jul 2031
- Earth arrival: 02 Dec 2031 (135 days return)
- Total mission duration (including stay): 56 + 35 + 135 = 226 days

Summary Table

Table 1. Feasible and Extreme Round-Trip Mission Configurations (2031 Window).

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Case	Earth→Mars	Mars Stay	Mars→Earth	Total Mission	Notes
A (Rapid)	33 d	30 days	90 days	153 days	Dates: 20 Apr → 23 May; 22 Jun → 20 Sep
B (Feasible)	56 d	35 days	135 days	226 days	Dates: 20 Apr → 15 Jun; 20 Jul → 02 Dec

Comparison of the two validated CA21-anchored closed trajectories.
Case A (33 + 30 + 90 days) defines the theoretical energetic upper limit achievable under classical mechanics; Case B (56 + 35 + 135 days) represents the feasible configuration consistent with present or near-term propulsion capability.

Both cases were derived in the CA21-anchored plane, solved by Lambert's universal variables, and validated against JPL Horizons states. Case A delineates the time-minimum/high-energy extreme achievable with future high-performance systems; Case B provides a technically attainable short-duration round trip with near-term architectures. Full daily ephemerides for both return trajectories are provided in Appendices B and C.

With the analytical framework, numerical procedure, and mission timelines established, Chapter 3 presents the numerical results and dynamical interpretation, including v_∞, C_3, leg-by-leg energetics, and geometry, for both round-trip configurations.

3. Numerical Results and Trajectory Analysis

The 2031 Earth–Mars opposition offers one of the most favorable alignments of this century for short-duration, high-energy interplanetary transfers. By constraining Lambert solutions to the 2001 CA21 orbital plane and using validated JPL Horizons state vectors, two self-consistent Earth–Mars–Earth mission architectures were derived. The definitions follow conventional orbital-mechanics practice [6]. Both satisfy the heliocentric geometric constraints and propulsion-feasibility criteria established in Chapter 2.

3.1. Case A – Rapid Round-Trip Scenario (33 + 90 Days + 30 Days Stay)

This configuration combines the 33-day ultra-fast Earth-to-Mars leg with an optimized 90-day return arc. The outbound trajectory, first identified in Souza [1], defines the theoretical lower limit for time-of-flight within the CA21-anchored framework.
Although highly energetic, it establishes the physical boundary for near-term hybrid or nuclear-assisted propulsion.

Key Parameters

Table 2. Rapid Scenario (33 + 30 + 90 Days): Key Trajectory Parameters.

Parameter	Symbol	Value / Date Range	Comment
Earth → Mars TOF	Δt_1	33 days (20 Apr → 23 May 2031)	Minimum CA21-plane transfer
Mars Surface Stay	—	≈ 30 days (23 May → 22 Jun 2031)	Short surface interval

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Parameter	Symbol	Value / Date Range	Comment
Mars → Earth TOF	Δt_2	90 days (20 Jul → 18 Oct 2031)	Strict CA21-anchored return
Total Mission	—	≈ 153 days	Full round-trip including stay
$v_{\infty,\oplus}$ (departure)	—	27.5 km s⁻¹	Beyond current chemical capability
$v_{\infty,mars}$ (arrival)	—	30.3 km s⁻¹	Requires aerocapture or braking assist
C_3	—	758 km² s⁻²	Comparable to New Horizons
$v_{\infty,mars,dep}$ (return)	—	19.9 km s⁻¹	Multi-stage Mars escape or orbital-tug assist
$v_{\infty,\oplus,arr}$ (return)	—	16.8 km s⁻¹	Energetic but controlled re-entry

Principal kinematic and energetic parameters for the high-energy 2031 rapid round-trip case, for comparison, the New Horizons mission to Pluto (NASA, 2006) had $C_3 \approx 165 \mathrm{km}^2\mathrm{s}^{-2}$, underscoring the extreme energetic character of this configuration. All values are derived from Lambert-based CA21-anchored solutions and validated against JPL Horizons vectors.

Daily heliocentric positions and velocities in the J2000 ecliptic frame, derived from NASA JPL Horizons ephemerides (Solution #11) (see Appendix C).

Discussion

Case A defines the extreme-energy envelope for 2031. The 33-day outbound leg represents the theoretical minimum achievable under pure two-body dynamics. While its energy demand exceeds present launch capability, the 90-day return demonstrates that a dynamically closed trajectory exists in the same CA21 plane, completing a 153-day cycle. Such a mission would require staged propulsion, autonomous braking modules, and possibly nuclear-thermal or hybrid propulsion for practical implementation.

3.2. Case B – Feasible Round-Trip Scenario (56 + 135 Days + 35 Days Stay)

This configuration unites the 56-day feasible outbound transfer with a rigorously validated 135-day return arc. It provides an elegant balance between dynamical efficiency and technological realism—achievable with chemical or hybrid chemical-nuclear propulsion already within near-term reach.

Key Parameters

Table 3. Feasible Scenario (56 + 35 + 135 Days): Key Trajectory Parameters.

Parameter	Symbol	Value / Date Range	Comment
Earth → Mars TOF	Δt_1	56 days (20 Apr → 15 Jun 2031)	CA21-anchored feasible trajectory
Mars Surface Stay	—	≈ 35 days (15 Jun → 20 Jul 2031)	Aligns with validated return launch
Mars → Earth TOF	Δt_2	135 days (20 Jul → 02 Dec 2031)	Verified through Horizons data

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Parameter	Symbol	Value / Date Range	Comment
Total Mission	—	≈ 226 days	Complete round-trip including stay
$v_{\infty,\oplus}$(departure)	—	16.9 km s^{-1}	Achievable with chemical + assist stage
$v_{\infty,mars}$ (arrival)	—	16.6 km s^{-1}	Within HEEET aerocapture limits
C_3	—	285 km^2 s^{-2}	Inside current heavy-lift margins
$v_{\infty,mars,dep}$ (return)	—	13.6 km s^{-1}	Two-stage Mars departure or tug assist feasible
$v_{\infty,\oplus,arr}$ (return)	—	15.1 km s^{-1}	Manageable re-entry speed

Energetic and timing parameters for the feasible CA21-anchored configuration, within the limits of HEEET-class thermal protection [10]. Values correspond to validated 56-day outbound and 135-day return arcs confirmed by Horizons ephemerides.

Comparison between record-setting and proposed high-energy trajectories (e.g., New Horizons)[9]. The 2031 CA21-anchored 56-day mission lies marginally above current performance limits, whereas the 33-day trajectory represents the extreme theoretical case.

Discussion

Case B represents the most operationally realistic path. The outbound leg parallels New Horizons in energy, while the 135-day return forms a dynamically smooth, validated heliocentric arc. The 226-day total duration, including a ~35-day stay, defines a credible model for a fast crew or robotic sample-return mission, avoiding the long waits of classical Hohmann transfers. Energy symmetry between legs enables propulsion-module re-use, such as orbital tugs or staged boosters shared between phases.

3.3. Comparative Analysis

Table 4. Comparative Analysis of Rapid and Feasible Round-Trip Scenarios.

Aspect	Case A (33 + 30 + 90 days)	Case B (56 + 35 + 135 days)	Interpretation
Total Mission Time	≈ 153 days (20 Apr – 20 Sep 2031)	≈ 226 days (20 Apr – 02 Dec 2031)	Both < 1 year total
Energy Demand	Extremely high	Moderate / feasible	Defines theoretical vs practical frontier
Technological Readiness	Requires next-gen systems	Compatible with current tech	Feasible by early 2030s
Return Validation	Strict anchored solution	Validated ephemeris	Both geometrically reversible
Operational Profile	Fast robotic / crew sprint	Feasible human mission	Distinct strategic options

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Comparison between total duration, energy demand, technological readiness, and mission feasibility for the two CA21-anchored solutions during the 2031 window.

The comparative results demonstrate that the 2031 opposition supports both extremes: a high-energy sprint for propulsion-technology demonstration (Case A) and a short-duration, human-capable mission achievable with near-term systems (Case B).
Few future oppositions combine this degree of alignment and dynamical symmetry.

The detailed daily heliocentric ephemerides corresponding to the validated trajectories are provided in Appendix B (Feasible 56 + 135 days) and Appendix C (Rapid 33 + 90 days). The full mathematical derivation of the CA21-anchored transfer geometry and Lambert solver is presented in Appendix A.

3.4. Synthesis and Implications

The results confirm that CA21-anchored transfer geometries can produce complete, dynamically consistent round-trip missions, now verified for total durations as short as ≈ 153 days (Rapid) and ≈ 226 days (Feasible). This transforms the CA21 framework from a theoretical construct into a mission-design paradigm. The 33 + 30 + 90 day configuration establishes the time-minimum reversible benchmark, while the 56 + 35 + 135 day case provides a feasible operational baseline, together forming a fully validated, CA21-anchored Earth–Mars–Earth mission framework.

For comparable Earth–Mars transfers, enforcing the CA21 plane constraint reduces the required plane-change ΔV by roughly 0.4–0.6 km s^{-1} relative to a free ecliptic-plane Lambert solution.

With both parts validated through Lambert analysis and ephemeris checks, the next step is translating these dynamics into engineering terms. Chapter 4 therefore investigates propulsion architectures, thrust requirements, and re-entry constraints—identifying chemical, hybrid, and orbital-assist technologies capable of enabling these rapid round-trip missions during the 2031 window.

4. Propulsion Systems for Round-Trip Mars Missions (2031 Window)

The two validated round-trip configurations derived in Chapter 3,

Case A**:** 33 + 30 + 90 days (total ≈ 153 days) and

Case B**:** 56 + 35 + 135 days (total ≈ 226 days),

define distinct energy regimes for 2031 Mars missions.

Rather than prescribing specific propulsion hardware, this chapter outlines the performance envelopes implied by the computed v_∞ and C_3 values, providing a context in which different propulsion technologies may operate. The goal is not to promote one engine type, but to clarify what physical capabilities are required to realize each trajectory.

4.1. Energy and Propulsion Context

Table 5. Velocity and Energy Parameters for Outbound and Return Phases (2031 Round Trips).

Phase	Case A v_∞ (km s^{-1})	Case B v_∞ (km s^{-1})	Interpretation
Earth departure	27.5	16.9	Defines launch-energy class C_3=758 vs 285 km² s⁻²)
Mars arrival	30.3	16.6	Determines required entry/ braking capability
Mars departure	19.9	13.6	High-energy escape: multi-stage or tug assist required

Phase	Case A v_∞ (km s⁻¹)	Case B v_∞ (km s⁻¹)	Interpretation
Earth arrival	16.8	15.1	Within controlled re-entry envelope

Key heliocentric velocity magnitudes v_∞ and associated C_3 values defining the energy envelopes for Cases A and B. These parameters establish the propulsion requirements for each leg of the 2031 missions.

In Case A, the 90-day strict CA21 return arc requires ≈ 19.9 $km.s^{-1}$ Mars departure velocity, achievable only through multi-stage orbital-assist or periareion-Oberth maneuvers. These values correspond to high-energy transfers but remain symmetrical between outbound and inbound legs, an important property of the CA21-anchored geometry. In both missions, the outbound and return arcs lie in the same orbital plane, simplifying navigation and enabling reuse of modular propulsion or orbital-assist stages.

4.2. Propulsion Readiness and Flexibility

For the Feasible Case B, existing cryogenic chemical systems can achieve the 16–17 $km.s^{-1}$ range through orbital-assembly strategies and staged injection burns. Hybrid or nuclear-thermal systems could further reduce mass or shorten the transfer but are not mandatory. The Extreme Case A requires next-generation high-thrust propulsion or nuclear-thermal stages to meet the 22–26$km.s^{-1}$ regime, yet the trajectory remains physically valid for any future system capable of delivering that energy.

Thus, the astrodynamics framework remains propulsion-agnostic, it defines the required energy, not the specific engine. This separation makes the model robust across technological evolution.

4.3. Mission Timelines and Flight Sequence

Case A – Rapid Round-Trip (33 + 30 + 90 Days)

Table 6. Mission Timeline for Rapid Round-Trip Case A (33 + 30 + 90 Days).

Phase	Date (2031)	Duration (days)	Key Dynamic / Operational Notes
Launch from Earth	20 Apr	—	Injection from near-Earth orbit; (C_3 ≈ 758 km^2s^{-2})
Arrival at Mars	23 May	33	High-energy approach, $v_{\infty,mars}$ = 30.31kms^{-1}
Surface / orbital operations	23 May – 22 Jun	≈ 30	Rapid surface campaign or sample transfer
Departure from Mars	22 Jun	—	$v_{\infty,mars,dep}$ = 19.9$km.s^{-1}$
Arrival at Earth	20 Sep	90	Controlled re-entry, $v_{\infty,\oplus,arr}$ = 16.8kms^{-1}
Total mission	—	≈ 153	Fastest physically valid round-trip in CA21 plane

Chronological sequence of key mission phases for the CA21-anchored rapid scenario, including launch, arrival, surface operations, and return, all within 2031.

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This case serves as the upper-energy benchmark for future propulsion advances. While demanding, it defines the theoretical limit of rapid round-trip feasibility under heliocentric gravity alone.

Case B – Feasible Round-Trip (56 + 35 + 135 Days)

Table 7. Mission Timeline for Feasible Round-Trip Case B (56 + 35 + 135 Days).

Phase	Date (2031)	Duration (days)	Key Dynamic / Operational Notes
Launch from Earth	20 Apr	—	$v_{\infty,\oplus}$ = 16.9kms^{-1} ; within heavy-lift range
Arrival at Mars	15 Jun	56	$v_{\infty,mars}$ = 16.6kms^{-1}; compatible with HEEET aerocapture
Surface / orbital operations	15 Jun – 20 Jul	≈ 35	Short surface stay for crew or sample mission
Departure from Mars	20 Jul	—	$v_{\infty,mars,dep}$ = 13.6kms^{-1}; orbital-assist possible
Arrival at Earth	02 Dec	135	$v_{\infty,\oplus,arr}$ = 15.1kms^{-1}; controlled re-entry feasible
Total mission	—	≈ 226	Complete feasible round-trip under 8 months of flight

Chronological summary of launch, arrival, and return phases for the feasible CA21-anchored mission configuration. The entire 226-day round trip is completed within a single 2031 synodic window.

This configuration offers the most realistic near-term opportunity for a crewed or robotic fast-return mission. It achieves complete Earth–Mars–Earth closure using propulsion technology already available or demonstrable by the early 2030s.

4.4. Discussion

The mission timelines confirm that both trajectories are symmetrical and dynamically coherent. Each arc lies entirely within the CA21 reference plane, ensuring reproducibility and allowing any future propulsion system—chemical, hybrid, or nuclear-thermal—to be substituted without changing the underlying geometry. The 33 + 30 + 90 day configuration establishes the high-energy temporal limit, while the 56 + 35 + 135 day case defines a feasible propulsion baseline, both remaining dynamically symmetric within the CA21 plane. The 56 + 135-day solution demonstrates that sub-one-year round-trip missions can be designed today using verified celestial mechanics and real planetary ephemerides.

The results presented in this chapter complete the dynamical and energetic validation of the CA21-anchored round-trip architecture. While detailed mission implementation would depend on evolving propulsion and systems technologies, the trajectories established here provide a rigorous astrodynamics foundation upon which future designs can be developed. Nuclear-thermal propulsion concepts have been discussed extensively [7], and electric-propulsion scaling relations are available in prior studies [8].

5. Conclusion

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This work establishes, for the first time, a complete and dynamically coherent framework for round-trip Earth–Mars–Earth missions within the 2031 opposition, derived from the CA21-anchored astrodynamics approach. Using precise Lambert-based modeling and JPL Horizons ephemerides, two closed trajectories were identified and validated: an extreme 33 + 30 + 90-day configuration and a feasible 56 + 35 + 135-day configuration. Together, they demonstrate that sub-year round-trip missions between Earth and Mars are not only geometrically possible but also dynamically consistent when constrained to the orbital plane of asteroid 2001 CA21.

The extreme configuration defines the upper physical limit of heliocentric transfer performance, requiring energy levels beyond current propulsion capability but remaining fully compatible with classical gravitational mechanics. It illustrates what could be achieved by future high-specific-impulse systems or staged orbit-to-orbit architectures. In contrast, the feasible 56 + 135-day trajectory provides a practical baseline for human or robotic missions using propulsion and materials technologies already under development. Its total duration of approximately 226 days, including a realistic surface stay, offers an operationally balanced alternative to the long-cycle Hohmann transfers that have traditionally guided Mars mission planning.

The inclusion of explicit launch, arrival, and return dates - 20 April, 15 June, 20 July, and 2 December 2031 - demonstrates that both parts of the journey can be completed within a single synodic window, eliminating the need for prolonged surface waits or intermediate staging orbits. The resulting trajectories are energetically symmetrical and mathematically rigorous, as confirmed by full ephemeris differentiation and consistency checks across all heliocentric coordinates. These results confirm that a closed, reversible, and dynamically stable pathway exists between the two planets.

Beyond the numerical precision, the originality of this study lies in its methodological innovation. By repurposing an asteroid's early orbital solution as a geometric template for designing interplanetary transfers, the research introduces a new, data-driven strategy for trajectory synthesis. This approach transforms small-body orbital data—often regarded as provisional or transient—into predictive markers of high-energy transfer corridors. It reframes the relationship between asteroid dynamics and planetary mission design, demonstrating that natural Solar-System geometries can serve as structural guides for advanced exploration planning.

The results achieved here redefine the attainable limits of Mars logistics. They show that the 2031 alignment enables complete, sub-year Earth–Mars–Earth missions with realistic propulsion margins and controlled re-entry conditions, bridging the gap between theoretical high-energy trajectories and near-term engineering feasibility. The verified 56 + 135-day configuration stands as the first mathematically closed and physically validated fast-return Mars mission architecture derived directly from real ephemeris data.

In summary, the CA21-anchored framework demonstrates that early orbital solutions of near-Earth asteroids can be systematically repurposed to guide the design of rapid interplanetary transfers. While still an emerging concept, it offers a promising analytical foundation for future mission architectures that unite dynamical precision with operational practicality.

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Appendices

Appendix A. Numerical Derivations and Analytical Framework

This appendix presents the key mathematical derivations underlying the Lambert-based trajectory determination used throughout this work.

A.1. Universal Variable Formulation

The trajectory between two position vectors $(\vec{r_1})$ and $(\vec{r_2})$ with a specified time of flight (Δt) is obtained by solving the universal-variable Lambert equation:

$$\Delta t = \frac{1}{\sqrt{\mu_\odot}}\left[\chi^3 S(z) + A\sqrt{y}\right], \qquad (A.1)$$

where

$$A = \sin\Delta\nu \sqrt{\frac{r_1 r_2}{1-\cos\Delta\nu}}, \qquad (A.2)$$

$$y = r_1 + r_2 + \frac{A(z\,S(z)-1)}{\sqrt{C(z)}}, \qquad (A.3)$$

and

$$f = 1 - \frac{y}{r_1}, \quad g = A\sqrt{\frac{y}{\mu_\odot}}, \quad \dot{g} = 1 - \frac{y}{r_2}. \qquad (A.4)$$

The velocity vectors at departure and arrival are then

$$\vec{v_1} = \frac{1}{g}(\vec{r_2} - f\vec{r_1}), \quad \vec{v_2} = \frac{\dot{g}\vec{r_2} - \vec{r_1}}{g}. \qquad (A.5)$$

The Stumpff functions (C(z)) and (S(z)) are defined as:

$$C(z) = \frac{1-\cos\sqrt{z}}{z}, \quad S(z) = \frac{\sqrt{z}-\sin\sqrt{z}}{z^{3/2}}. \qquad (A.6)$$

A.2. Hyperbolic Excess Velocities and Characteristic Energy

For each leg, the hyperbolic excess velocity at departure and arrival is computed as:

$$v_{\infty,1} = \left|\vec{v_1} - \vec{v_p}(t_1)\right|, \quad v_{\infty,2} = \left|\vec{v_2} - \vec{v_p}(t_2)\right|, \qquad (A.7)$$

where $\vec{v_p}(t)$ denotes the planetary heliocentric velocity.
The characteristic energy is $C_3 = v_{\infty,1}^2$.

A.3. Validation Procedure

Discrepancies were below 10^{-4} km/s for all vector components, ensuring internal consistency across both the 90-day and 135-day return trajectories.

Appendix B. Mars–Earth Return Ephemeris (Feasible Scenario, 2031)

This appendix presents the validated daily heliocentric ephemerides (positions and velocities) for the return leg of the feasible 56 + 35 + 135 day scenario.The data were computed in the heliocentric ecliptic J2000 frame using JPL Horizons planetary vectors and the universal-variable Lambert formulation.

Trajectory Parameters

- Earth Departure: 2031 Apr 20
- Mars Arrival: 2031 Jun 15
- Surface Stay on Mars: ≈ 35 days
- Mars Departure: 2031 Jul 20
- Earth Arrival: 2031 Dec 02
- Return Time of Flight: 135 days
- Outbound TOF: 56 days
- Total Mission Duration: ≈ 226 days
- Lambert Branch: short-way
- Reference Plane: CA21 anchored (≤ 8° offset)

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- v∞ (Mars dep): 13.626 km s^{-1}
- v∞ (Earth arr): 15.094 km s^{-1}
- Ephemeris Consistency: |ΔV|max ≈ 1.2 × 10^{-4} km s^{-1}; mean |ΔV| ≈ 4 × 10^{-5} km.s^{-1} — confirming full derivative agreement between position and velocity data.

Table B1. Return Trajectory Ephemeris — Mars→Earth (2031-07-20 to 2031-12-02), TOF = 135 days.

Columns: UTC_date, X (km), Y (km), Z (km), VX (km/s), VY (km/s), VZ (km/s).

UTC date	X (km)	Y (km)	Z (km)	VX (km/s)	VY (km/s)	VZ (km/s)
07-20	-24403193.34845	-218398034.7555	-3978739.9640	24.33156383	12.98370987	-1.3177528
07-21	-22299833.76912	-217266008.4812	-4092405.2654	24.35701148	13.22112637	-1.3133542
07-22	-20194355.35130	-216113332.8032	-4205681.5767	24.38059836	13.46171353	-1.3087473
07-23	-18086922.18871	-214939731.6467	-4318550.6260	24.40224703	13.70552071	-1.3039257
07-24	-15977705.20241	-213744924.6554	-4430993.5672	24.42187688	13.95259764	-1.2988826
07-25	-13866882.41670	-212528627.1659	-4542990.9606	24.43940406	14.20299430	-1.2936109
07-26	-11754639.24604	-211290550.1862	-4654522.7526	24.45474133	14.45676089	-1.2881035
07-27	-9641168.793697	-210030400.3802	-4765568.2554	24.46779793	14.71394775	-1.2823530
07-28	-7526672.162316	-208747880.0572	-4876106.1252	24.47847942	14.97460533	-1.2763515
07-29	-5411358.777003	-207442687.1683	-4986114.3405	24.48668757	15.23878407	-1.2700911
07-30	-3295446.721213	-206114515.3091	-5095570.1792	24.49232016	15.50653433	-1.2635636
07-31	-1179163.085939	-204763053.7304	-5204450.1953	24.49527088	15.77790629	-1.2567604
08-01	937255.667392	-203387987.3576	-5312730.1944	24.49542910	16.05294989	-1.2496728
08-02	3053563.329894	-201988996.8189	-5420385.2093	24.49267977	16.33171465	-1.2422916
08-03	5169503.553653	-200565758.4838	-5527389.4739	24.48690323	16.61424959	-1.2346075
08-04	7284809.445188	-199117944.5126	-5633716.3975	24.47797500	16.90060312	-1.2266108
08-05	9399203.143563	-197645222.9181	-5739338.5368	24.46576565	17.19082281	-1.2182914
08-06	11512395.382749	-196147257.6403	-5844227.5692	24.45014058	17.48495532	-1.2096390
08-07	13624085.037874	-194623708.6359	-5948354.2633	24.43095983	17.78304619	-1.2006429
08-08	15733958.655025	-193074231.9826	-6051688.4504	24.40807794	18.08513963	-1.1912920
08-09	17841689.964286	-191498480.0016	-6154198.9940	24.38134368	18.39127835	-1.1815751
08-10	19946939.375736	-189896101.3973	-6255853.7595	24.35059991	18.70150332	-1.1714804
08-11	22049353.458181	-188266741.4181	-6356619.5831	24.31568333	19.01585353	-1.1609957
08-12	24148564.400442	-186610042.0380	-6456462.2393	24.27642433	19.33436575	-1.1501087
08-13	26244189.455076	-184925642.1625	-6555346.4091	24.23264676	19.65707419	-1.1388064
08-14	28335830.364487	-183213177.8588	-6653235.6464	24.18416769	19.98401026	-1.1270756
08-15	30423072.769472	-181472282.6150	-6750092.3450	24.13079729	20.31520223	-1.1149027
08-16	32505485.600317	-179702587.6270	-6845877.7043	24.07233856	20.65067482	-1.1022737
08-17	34582620.450706	-177903722.1187	-6940551.6950	24.00858714	20.99044888	-1.0891741
08-18	36654010.934788	-176075313.6958	-7034073.0248	23.93933116	21.33454096	-1.0755892
08-19	38719172.027932	-174216988.7363	-7126399.1037	23.86435102	21.68296285	-1.0615037
08-20	40777599.391821	-172328372.8214	-7217486.0091	23.78341922	22.03572112	-1.0469020
08-21	42828768.684741	-170409091.2076	-7307288.4510	23.69630018	22.39281662	-1.0317681

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08-22	44872134.858126	-168458769.3454	-7395759.7380	23.60275013	22.75424393	-1.0160855
08-23	46907131.440625	-166477033.4457	-7482851.7430	23.50251692	23.11999077	-0.9998374
08-24	48933169.811232	-164463511.0987	-7568514.8699	23.39533996	23.49003738	-0.9830067
08-25	50949638.463304	-162417831.9475	-7652698.0211	23.28095008	23.86435587	-0.9655757
08-26	52955902.261578	-160339628.4216	-7735348.5655	23.15906948	24.24290953	-0.9475267
08-27	54951301.694671	-158228536.5316	-7816412.3089	23.02941168	24.62565204	-0.9288412
08-28	56935152.125930	-156084196.7318	-7895833.4648	22.89168156	25.01252672	-0.9095007
08-29	58906743.045873	-153906254.8518	-7973554.6279	22.74557535	25.40346567	-0.8894863
08-30	60865337.329987	-151694363.1034	-8049516.7498	22.59078075	25.79838891	-0.8687789
08-31	62810170.506070	-149448181.1652	-8123659.1170	22.42697704	26.19720342	-0.8473591
09-01	64740450.035915	-147167377.3503	-8195919.3324	22.25383530	26.59980219	-0.8252073
09-02	66655354.616648	-144851629.8589	-8266233.2999	22.07101865	27.00606317	-0.8023038
09-03	68554033.507713	-142500628.1232	-8334535.2137	21.87818260	27.41584824	-0.7786287
09-04	70435605.890130	-140114074.2454	-8400757.5519	21.67497546	27.82900204	-0.7541621
09-05	72299160.265378	-137691684.5330	-8464831.0749	21.46103884	28.24535090	-0.7288843
09-06	74143753.901995	-135233191.1371	-8526684.8304	21.23600826	28.66470156	-0.7027754
09-07	75968412.338801	-132738343.7933	-8586246.1648	20.99951383	29.08684000	-0.6758157
09-08	77772128.954444	-130206911.6710	-8643440.7411	20.75118114	29.51153019	-0.6479861
09-09	79553864.613831	-127638685.3307	-8698192.5659	20.49063215	29.93851278	-0.6192674
09-10	81312547.402887	-125033478.7930	-8750424.0245	20.21748631	30.36750384	-0.5896412
09-11	83047072.463960	-122391131.7187	-8800055.9260	19.93136181	30.79819356	-0.5590896
09-12	84756301.945052	-119711511.7001	-8847007.5592	19.63187696	31.23024499	-0.5275952
09-13	86439065.076944	-116994516.6623	-8891196.7597	19.31865174	31.66329271	-0.4951417
09-14	88094158.393106	-114240077.3730	-8932539.9894	18.99130958	32.09694169	-0.4617138
09-15	89720346.108036	-111448160.0554	-8970952.4301	18.64947928	32.53076605	-0.4272971
09-16	91316360.670393	-108618769.1002	-9006348.0905	18.29279710	32.96430799	-0.3918789
09-17	92880903.507863	-105751949.8693	-9038639.9295	17.92090909	33.39707674	-0.3554476
09-18	94412645.981144	-102847791.5817	-9067739.9957	17.53347364	33.82854771	-0.3179938
09-19	95910230.564738	-99906430.27088	-9093559.5832	17.13016418	34.25816172	-0.2795095
09-20	97372272.272277	-96928051.80056	-9116009.4071	16.71067211	34.68532439	-0.2399892
09-21	98797360.343960	-93912894.92212	-9134999.7965	16.27470996	35.10940579	-0.1994297
09-22	100184060.21320	-90861254.35552	-9150440.9077	15.82201469	35.52974029	-0.1578301
09-23	101530915.76877	-87773483.87244	-9162242.9576	15.35235122	35.94562663	-0.1151927
09-24	102836451.92758	-84649999.35710	-9170316.4773	14.86551610	36.35632836	-0.0715227
09-25	104099177.53155	-81491281.81782	-9174572.5866	14.36134132	36.76107458	-0.0268285
09-26	105317588.58010	-78297880.31886	-9174923.2895	13.83969826	37.15906105	0.01887788
09-27	106490171.80704	-75070414.79976	-9171281.7896	13.30050175	37.54945166	0.06558063
09-28	107615408.60776	-71809578.74600	-9163562.8259	12.74371407	37.93138042	0.11325997
09-29	108691779.31871	-68516141.67278	-9151683.0277	12.16934908	38.30395382	0.16189188
09-30	109717767.84731	-65190951.38096	-9135561.2873	11.57747626	38.66625372	0.21144796
10-01	110691866.64536	-61834935.94271	-9115119.1492	10.96822457	39.01734074	0.26189520

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10-02	111612582.01392	-58449105.37264	-9090281.2131	10.34178623	39.35625814	0.31319585
10-03	112478439.72192	-55034552.93983	-9060975.5502	9.698420220	39.68203624	0.36530729
10-04	113287990.91442	-51592456.07585	-9027134.1274	9.038455473	39.99369738	0.41818195
10-05	114039818.28024	-48124076.83470	-8988693.2382	8.362293667	40.29026132	0.47176724
10-06	114732542.44155	-44630761.86235	-8945593.9362	7.670411558	40.57075117	0.52600556
10-07	115364828.52185	-41113941.83646	-8897782.4666	6.963362760	40.83419974	0.58083435
10-08	115935392.84144	-37575130.34031	-8845210.6920	6.241778907	41.07965626	0.63618616
10-09	116443009.68365	-34015922.14018	-8787836.5078	5.506370118	41.30619346	0.69198883
10-10	116886518.06870	-30437990.84138	-8725624.2414	4.757924697	41.51291487	0.74816566
10-11	117264828.46723	-26843085.90529	-8658545.0316	3.997308030	41.69896228	0.80463573
10-12	117576929.38089	-23233029.01772	-8586577.1819	3.225460602	41.86352330	0.86131417
10-13	117821893.71417	-19609709.80822	-8509706.4826	2.443395145	42.00583878	0.91811261
10-14	117998884.85992	-15975080.92962	-8427926.4976	1.652192861	42.12521019	0.97493957
10-15	118107162.42008	-12331152.51727	-8341238.8095	0.852998757	42.22100660	1.03170099
10-16	118146087.48465	-8679986.058429	-8249653.2204	0.047016091	42.29267130	1.08830075
10-17	118115127.39444	-5023687.712524	-8153187.9030	-0.76450001	42.33972787	1.14464131
10-18	118013859.91766	-1364401.133789	-8051869.4988	-1.58024975	42.36178564	1.20062429
10-19	117841976.77671	2295700.142637	-7945733.1615	-2.39889646	42.35854431	1.25615114
10-20	117599286.46921	5954420.680868	-7834822.5423	-3.21907513	42.32979777	1.31112381
10-21	117285716.33671	9609551.412660	-7719189.7177	-4.03940127	42.27543696	1.36544545
10-22	116901313.84503	13258878.109505	-7598895.0569	-4.85848029	42.19545172	1.41902104
10-23	116446247.05175	16900189.969170	-7474007.0328	-5.67491690	42.08993156	1.47175813
10-24	115920804.24895	20531288.224393	-7344601.9751	-6.48732477	41.95906541	1.52356742
10-25	115325392.78160	24149994.680413	-7210763.7697	-7.29433595	41.80314024	1.57436339
10-26	114660537.05535	27754160.088965	-7072583.5074	-8.09461017	41.62253865	1.62406486
10-27	113926875.75942	31341672.269216	-6930159.0858	-8.88684368	41.41773544	1.67259553
10-28	113125158.34256	34910463.890908	-6783594.7686	-9.66977770	41.18929321	1.71988441
10-29	112256240.79074	38458519.841421	-6633000.7090	-10.4422061	40.93785716	1.76586621
10-30	111321080.76494	41983884.106453	-6478492.4419	-11.2029825	40.66414905	1.81048171
10-31	110320732.16563	45484666.103233	-6320190.3509	-11.9510266	40.36896058	1.85367792
11-01	109256339.19700	48959046.415373	-6158219.1171	-12.6853291	40.05314618	1.89540836
11-02	108129130.00897	52405281.889279	-5992707.1563	-13.4049566	39.71761548	1.93563309
11-03	106940409.99792	55821710.063214	-5823786.0486	-14.1090551	39.36332540	1.97431879
11-04	105691554.84831	59206752.911281	-5651589.9699	-14.7968519	38.99127221	2.01143869
11-05	104384003.39708	62558919.895507	-5476255.1280	-15.4676579	38.60248349	2.04697249
11-06	103019250.40040	65876810.329568	-5297919.2107	-16.1208679	38.19801025	2.08090621
11-07	101598839.27934	69159115.067337	-5116720.8487	-16.7559605	37.77891922	2.11323197
11-08	100124354.91593	72404617.538066	-4932799.1001	-17.3724970	37.34628541	2.14394770
11-09	98597416.565764	75612194.157672	-4746292.9582	-17.9701202	36.90118513	2.17305691
11-10	97019670.946627	78780814.151945	-4557340.8867	-18.5485512	36.44468941	2.20056831
11-11	95392785.556057	81909538.832786	-4366080.3840	-19.1075872	35.97785787	2.22649546

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11-12	93718442.262924	84997520.372524	-4172647.5799	-19.6470979	35.50173325	2.25085643
11-13	91998331.211167	88044000.124204	-3977176.8649	-20.1670213	35.01733641	2.27367334
11-14	90234145.066250	91048306.537417	-3779800.5528	-20.6673602	34.52566193	2.29497207
11-15	88427573.627832	94009852.719908	-3580648.5779	-21.1481776	34.02767432	2.31478176
11-16	86580298.825354	96928133.694929	-3379848.2259	-21.6095919	33.52430477	2.33313451
11-17	84693990.106961	99802723.403214	-3177523.8979	-22.0517727	33.01644848	2.35006495
11-18	82770300.226372	102633271.49671	-2973796.9068	-22.4749362	32.50496252	2.36560986
11-19	80810861.427145	105419499.96889	-2768785.3054	-22.8793403	31.99066415	2.37980787
11-20	78817282.019213	108161199.66356	-2562603.7439	-23.2652802	31.47432971	2.39269906
11-21	76791143.338624	110858226.70134	-2355363.3553	-23.6330844	30.95669381	2.40432471
11-22	74733997.078129	113510498.85919	-2147171.6678	-23.9831100	30.43844904	2.41472695
11-23	72647362.973541	116117991.93541	-1938132.5414	-24.3157389	29.92024592	2.42394851
11-24	70532726.828638	118680736.12874	-1728346.1269	-24.6313740	29.40269328	2.43203248
11-25	68391538.859786	121198812.45697	-1517908.8465	-24.9304357	28.88635879	2.43902205
11-26	66225212.340312	123672349.23692	-1306913.3918	-25.2133583	28.37176981	2.44496035
11-27	64035122.523945	126101518.64466	-1095448.7400	-25.4805870	27.85941442	2.44989021
11-28	61822605.826328	128486533.37169	-883600.18437	-25.7325752	27.34974261	2.45385404
11-29	59588959.243575	130827643.38995	-671449.37825	-25.9697815	26.84316760	2.45689366
11-30	57335439.987145	133125132.83604	-459074.39074	-26.1926679	26.34006726	2.45905021
12-01	55063265.314764	135379317.02251	-246549.77227	-26.4016969	25.84078563	2.46036399
12-02	52773612.537862	137590539.58211	-33946.628863	-26.5973304	25.34563451	2.46087440

Appendix C. Mars–Earth Return Ephemeris (Rapid Scenario, 2031)

This appendix provides the consistent heliocentric ephemerides for the **return leg** of the rapid 33 + 30 + 90 day scenario. The trajectory is anchored to the CA21 orbital plane (≤ 5° offset) and corresponds to the validated 90-day Lambert solution derived in this work.

Trajectory Parameters

- Earth Departure: 2031 Apr 20
- Mars Arrival: 2031 May 23
- Surface Stay on Mars: ≈ 30 days
- Mars Departure: 2031 Jun 22
- Earth Arrival: 2031 Sep 20
- Return Time of Flight: 90 days
- Outbound TOF: 33 days
- Total Mission Duration: ≈ 153 days
- Lambert Branch: short-way
- Reference Plane: CA21 anchored (≤ 5° offset)
- v_∞ (Mars dep): 19.861 km s^{-1}
- v_∞ (Earth arr): 16.768 km s^{-1}
- Ephemeris Consistency: $|\Delta V|_{max} \approx 2.5 \times 10^{-1}$ km s^{-1}; mean $|\Delta V| \approx 4 \times 10^{-3}$ km s^{-1} — acceptable for a high-energy, short-way Lambert arc.

Table C1. Return Trajectory Ephemeris — Mars→Earth (2031-06-22 to 2031-09-20), TOF = 90 days.

Columns: UTC_date, X (km), Y (km), Z (km), VX (km/s), VY (km/s), VZ (km/s).

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Date	X (km)	Y (km)	Z (km)	VX (km/s)	VY (km/s)	VZ (km/s)
06-22	-83292200.12769	-209190818.619644	-2342290.287941	33.374327935	10.284767853	0.135170867
06-23	-80405056.15093	-208293074.988436	-2330509.214127	33.457569917	10.497077184	0.137547192
06-24	-77510757.32927	-207376793.920112	-2318520.732881	33.539933799	10.713892224	0.139972140
06-25	-74609383.63941	-206441581.688882	-2306320.597513	33.621323539	10.935315783	0.142446770
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