Interstellar Interceptors

Mission design for rendezvous with objects in hyperbolic orbits

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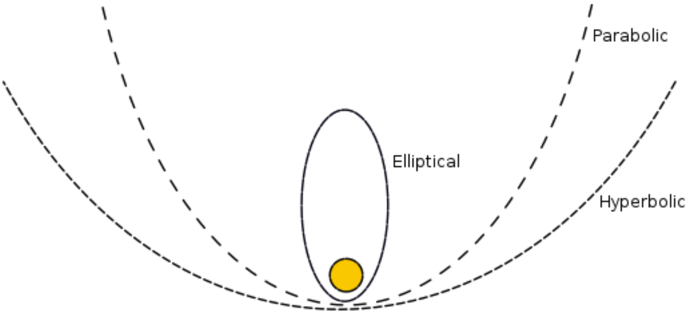
What are interstellar objects?

Definition

Interstellar objects (ISOs) are asteroids, comets or planetary bodies moving through interstellar medium (ISM) without being gravitationally bound to a star.



ISOs follow hyperbolic orbits

Why are interstellar objects important?

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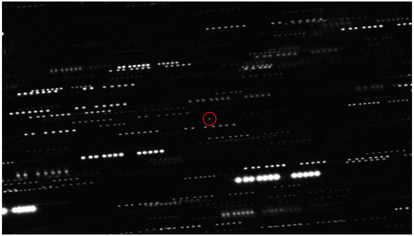
Motivation of this work

Devise orbits for rendezvous with ISOs to study their physical properties.

Discovered interstellar objects

There are two confirmed ISOs to this day:



1I/'Oumuamua

2I/Borisov

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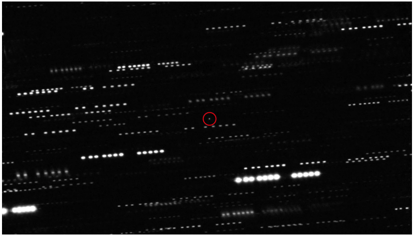


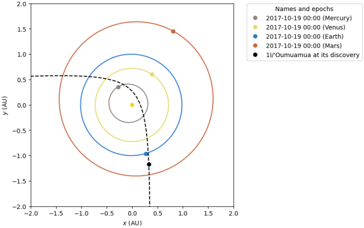
1I/'Oumuamua

2I/Borisov

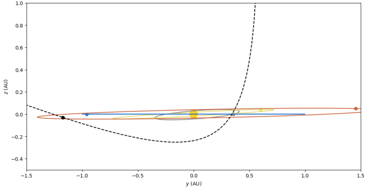
These interlopers present the following orbit attributes:

- Hyperbolic orbits
- High relative velocity
- High inclination w.r.t. the ecliptic plane
- Discovered close to the direction of the Solar Apex

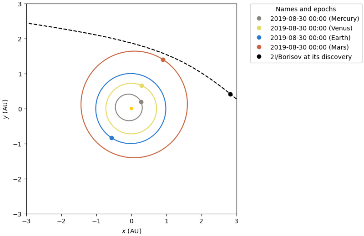
Orbits of 1I/’Oumuamua and 2I/Borisov



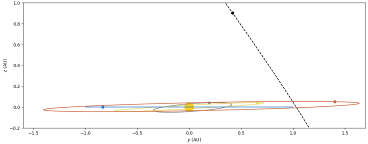
1I/’Oumuamua orbit top view



1I/’Oumuamua orbit side view



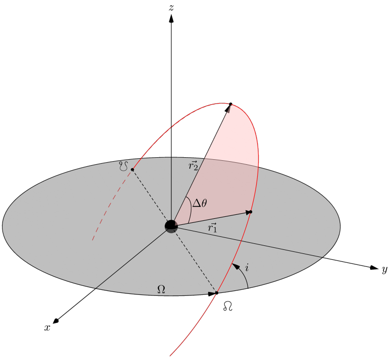
2I/Borisov orbit top view



2I/Borisov orbit side view

Navigating through space: the Lambert's problem

Lambert's problem is the Boundary Value Problem (BVP) in the context of the restricted two-body problem dynamics.



Geometry of the Lambert's problem

$$\ddot{\vec{r}} = -\frac{\mu}{r^3}\vec{r} \qquad \begin{cases} \vec{r}\,(t_1) = \vec{r_1} \\ \vec{r}\,(t_2) = \vec{r_2} \end{cases}$$

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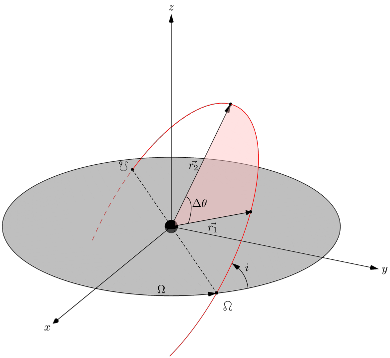

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Solve for the orbit which passes through $\vec{r_1}$ and $\vec{r_2}$ over a finite amount of time $\Delta t = t_2 - t_1$.

Estimating the cost of the maneuver using the C_3 energy

Lambert's problem computes the initial velocity $\vec{v_1}$ and final velocity $\vec{v_2}$ of the orbit.

- First impulse: $\Delta v_1 = \|v_1 - v_{\text{origin}}\|$
- Last impulse: $\Delta v_2 = \|v_2 - v_{\text{iso}}\|$

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The total cost of the maneuver is $\Delta v = \Delta v_1 + \Delta v_2$. This relates with the fuel mass via the Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln\left(\frac{m_0}{m_f}\right)$$

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The characteristic energy for hyperbolic orbits C_3 is defined as:

$$C_3 = v_\infty^2$$

Minimizing the cost of the maneuver

Porkchop plots are used to find the optimal launch and arrival dates by solving Lambert's problem for a variety of trajectories.

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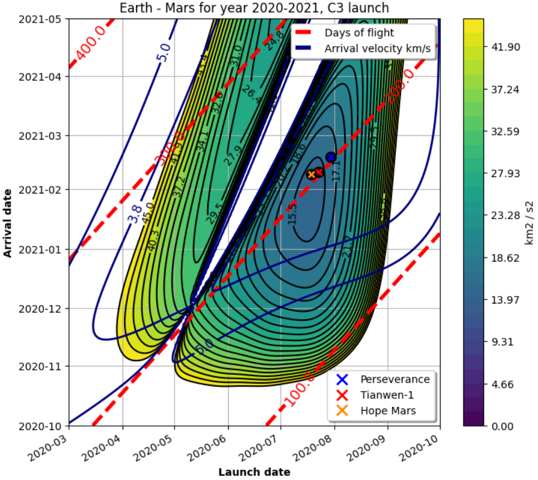

Porkchop plot between Earth and Mars

Analyzed scenarios

The analyzed scenarios in this work for each discovered ISO include:

- Direct transfer between the Earth and the ISO
- Direct transfer between the L2 point and the ISO

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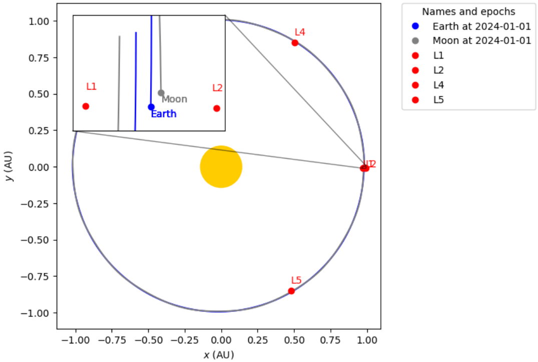
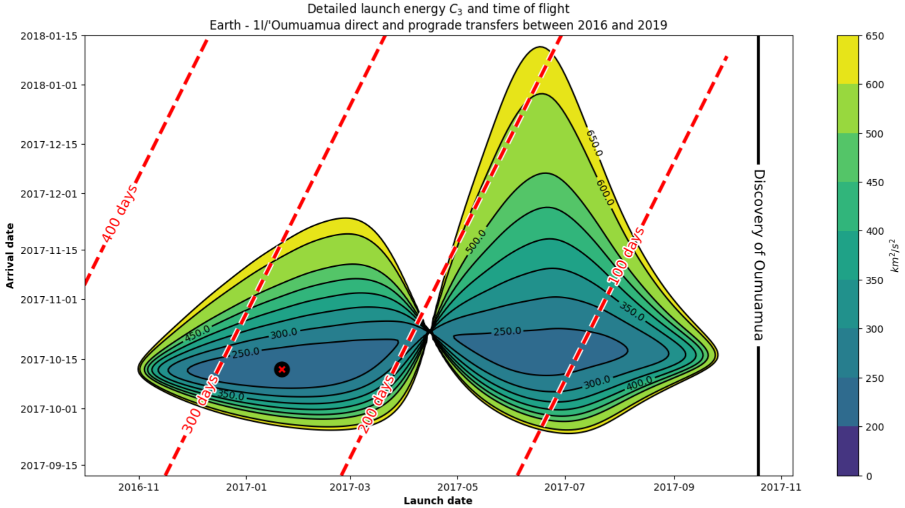


Lagrange points for the Sun Earth-Moon system

1I/'Oumuamua: direct prograde transfer from Earth



Direct transfer from Earth

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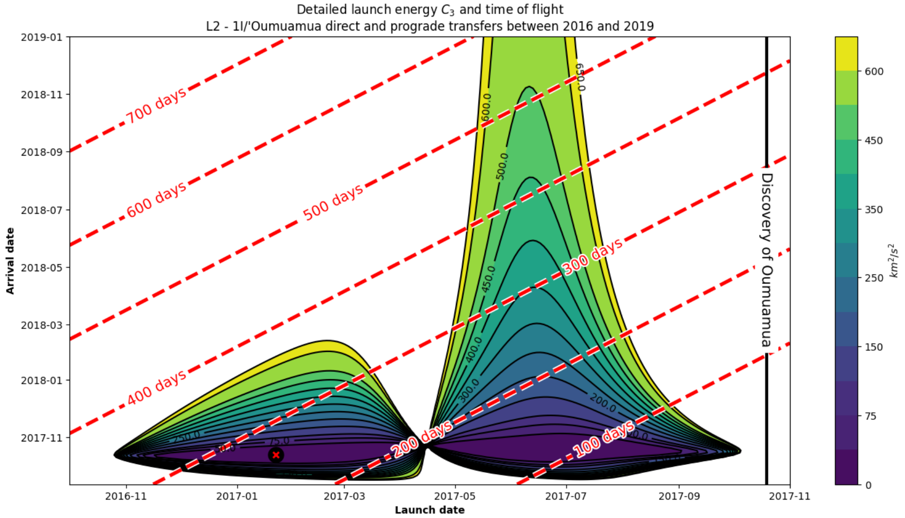


Direct transfer from L2

1I/'Oumuamua: summary of results

Δv launch Earth [km/s]	Δv launch L2 [km/s]	Reduction [%]
13.85	3.80	72.56

Launch energy comparison

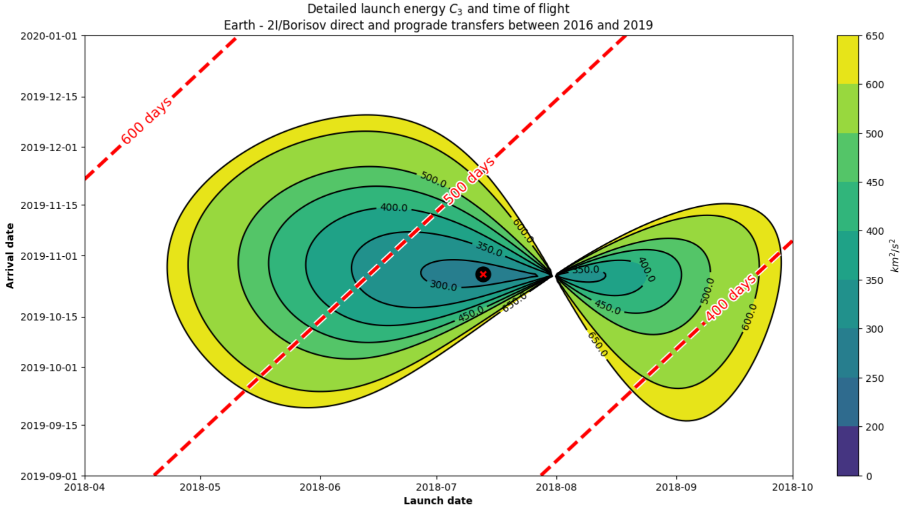
ΔV arrival Earth [km/s]	ΔV arrival L2 [km/s]	Reduction [%]
62.33	61.46	1.40

Arrival velocity comparison

C_3 launch Earth [km^2/s^2]	C_3 launch L2 [km^2/s^2]	Reduction [%]
192.00	14.41	92.51

Characteristic energy comparison

2I/Borisov: direct prograde transfer from Earth



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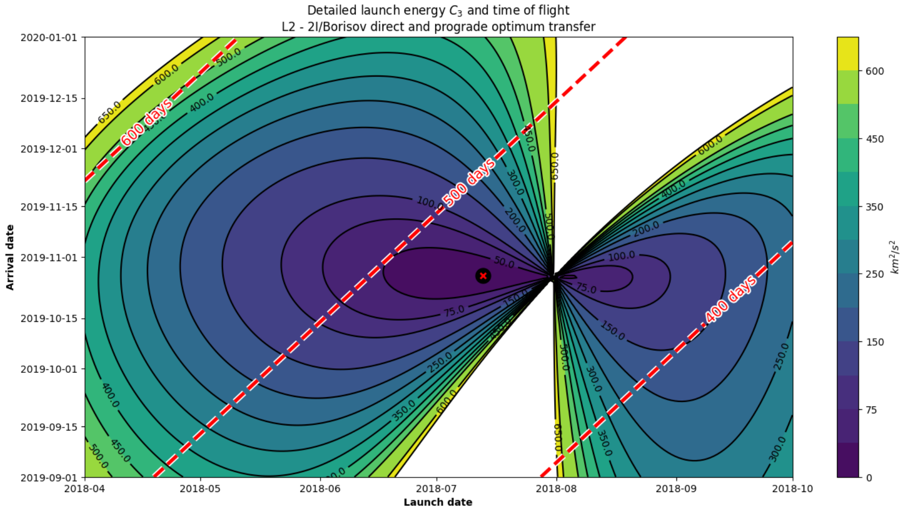

Direct transfer from Earth

2I/Borisov: summary of results

Δv launch Earth [km/s]	Δv launch L2 [km/s]	Reduction [%]
16.90	5.85	65.38

Launch energy comparison

ΔV arrival Earth [km/s]	ΔV arrival L2 [km/s]	Reduction [%]
33.00	33.02	-0.06

Arrival velocity comparison

C_3 launch Earth [km^2/s^2]	C_3 launch L2 [km^2/s^2]	Reduction [%]
286.00	34.30	88.08

Characteristic energy comparison

Conclusions

L2 as the optimal launch point

Launching an intercepting spacecraft from L2 is more fuel efficient. These results agree with the ones presented by the Comet Interceptor mission.

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Other advantages of launching from L2 include:

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- Possibility of studying long period comets if no ISO is found

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Further studies

A simulation considering multiple ISOs orbits could find optimum solutions for a variety of scenarios. Multiple-gravity assists with deep space maneuvers could be considered to further reduce the cost of the mission.