Mission to Sedna with a Solar Sail exploiting thermal desorption of coatings

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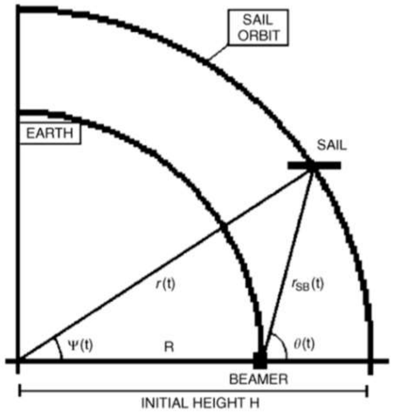
Outline

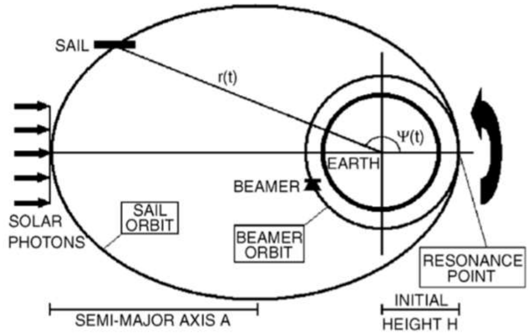
- Concepts of acceleration using thermal desorption
- Sail's temperature dependence on heliocentric distance
- Solar sailing: highlights
- Why Sedna
- Scenarios
- Conclusions and future development

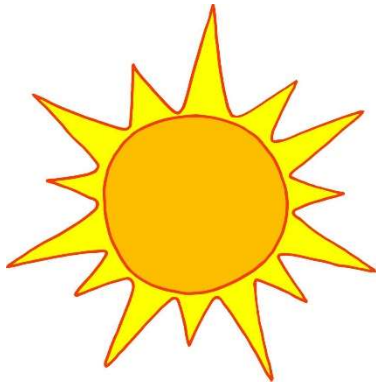
Thermal desorption

- physical process of **mass loss**;
- dominates above temperatures of 300–600 °C;
- provides **additional thrust** as heating liberates atoms, embedded on the surface of a solar sail;
- suggested by Benford & Benford, 2005 using beam-powered microwave pulse for heating (from Earth or from orbit) ;
- For extrasolar space exploration it might be very convenient to take advantage of **space environmental effects** such as **solar radiation heating**;
- The solar sail **naturally gains temperature through the absorption of solar radiation**.

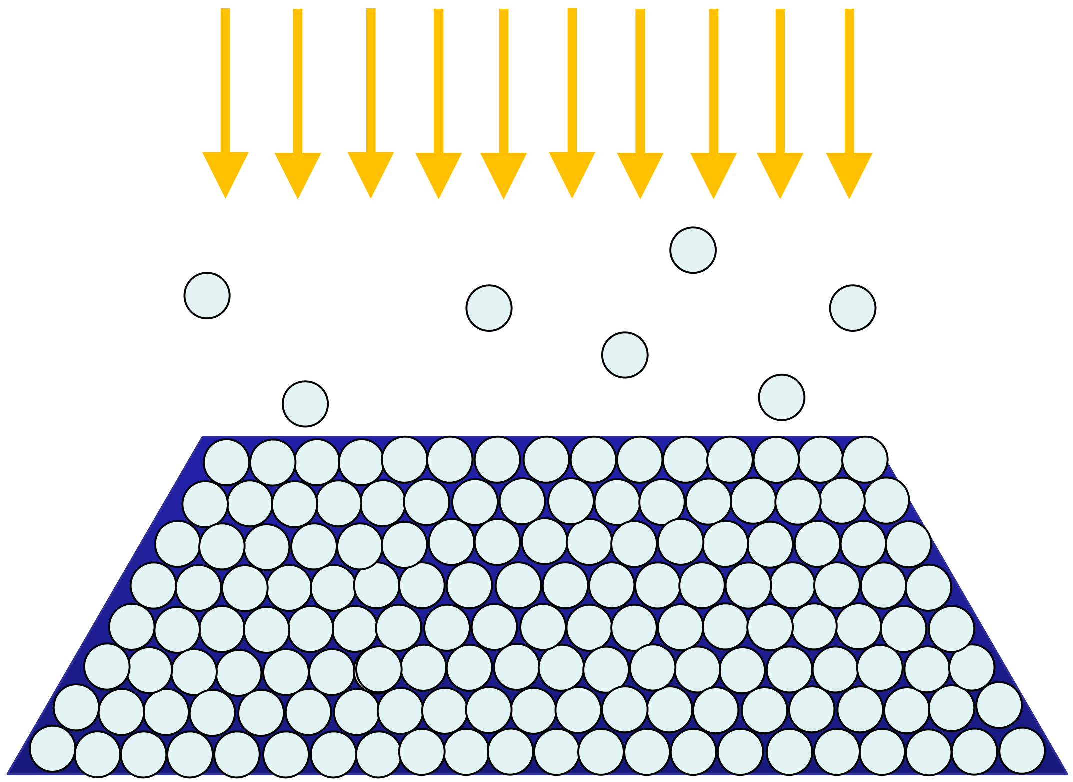
Acceleration of sails by thermal desorption is not a new idea, but it is new to apply this idea to the solar sail that naturally gains temperature through the absorption of solar radiation.







Sun-Heating Desorption-Assisted Solar Sail



Atoms liberated by heating provide additional thrust;

Short times -> impulsive maneuver

Thermal desorption: the chemical process

- If **N** particles of molecular mass $\mathbf{m_p}$ leave the sail surface at velocity $\mathbf{v_{th}}$, for the law of conservation of total momentum, the sail of mass **m** will move in the opposite direction with velocity **v**:

$$v = (N\, m_p\, v_{th})\,/m.$$

- The thermal velocity can be found with the Maxwell speeds distribution:

$$v_{th} = \sqrt{\frac{8k_B T}{\pi m_p}}.$$

$k_B = 1.38 \cdot 10^{-23}$ J/K

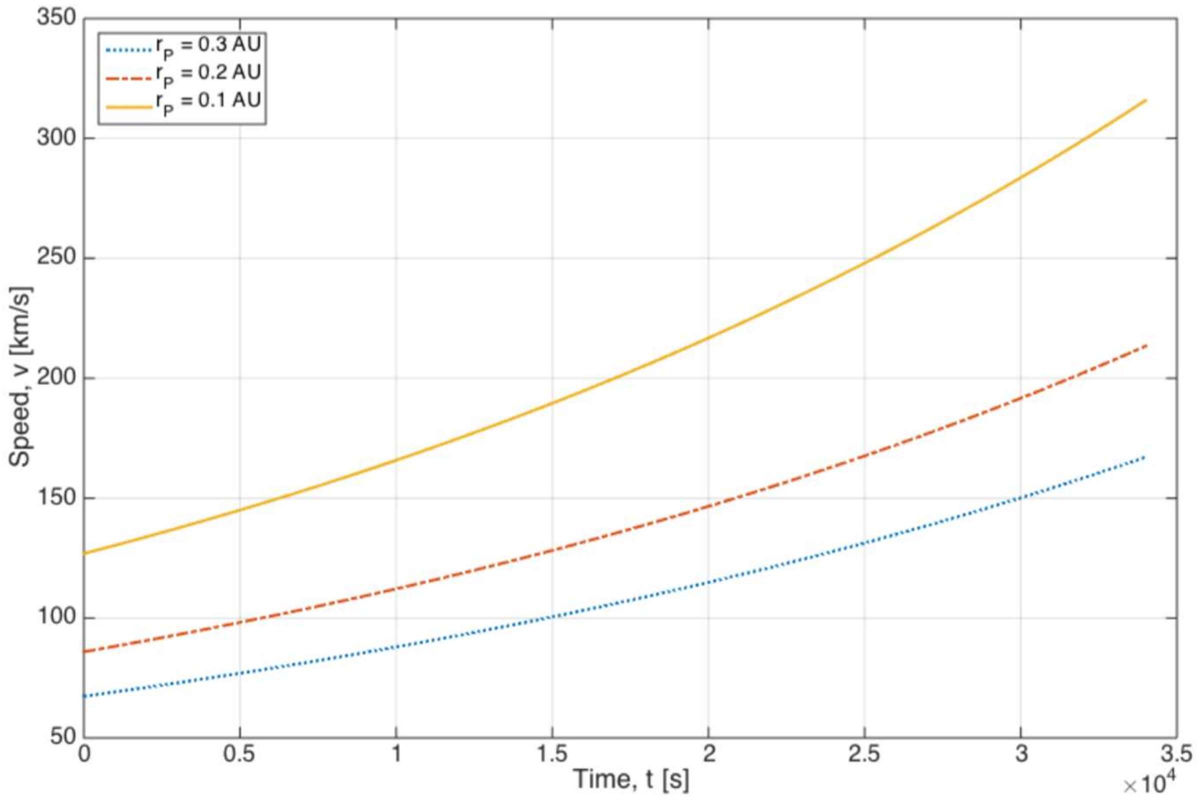
- And, finally, the acceleration due to desorption a_D is:

$$a_D = \frac{\sqrt{8\pi\, N\, m_p\, T}}{m\, t}$$

t = time of desorption

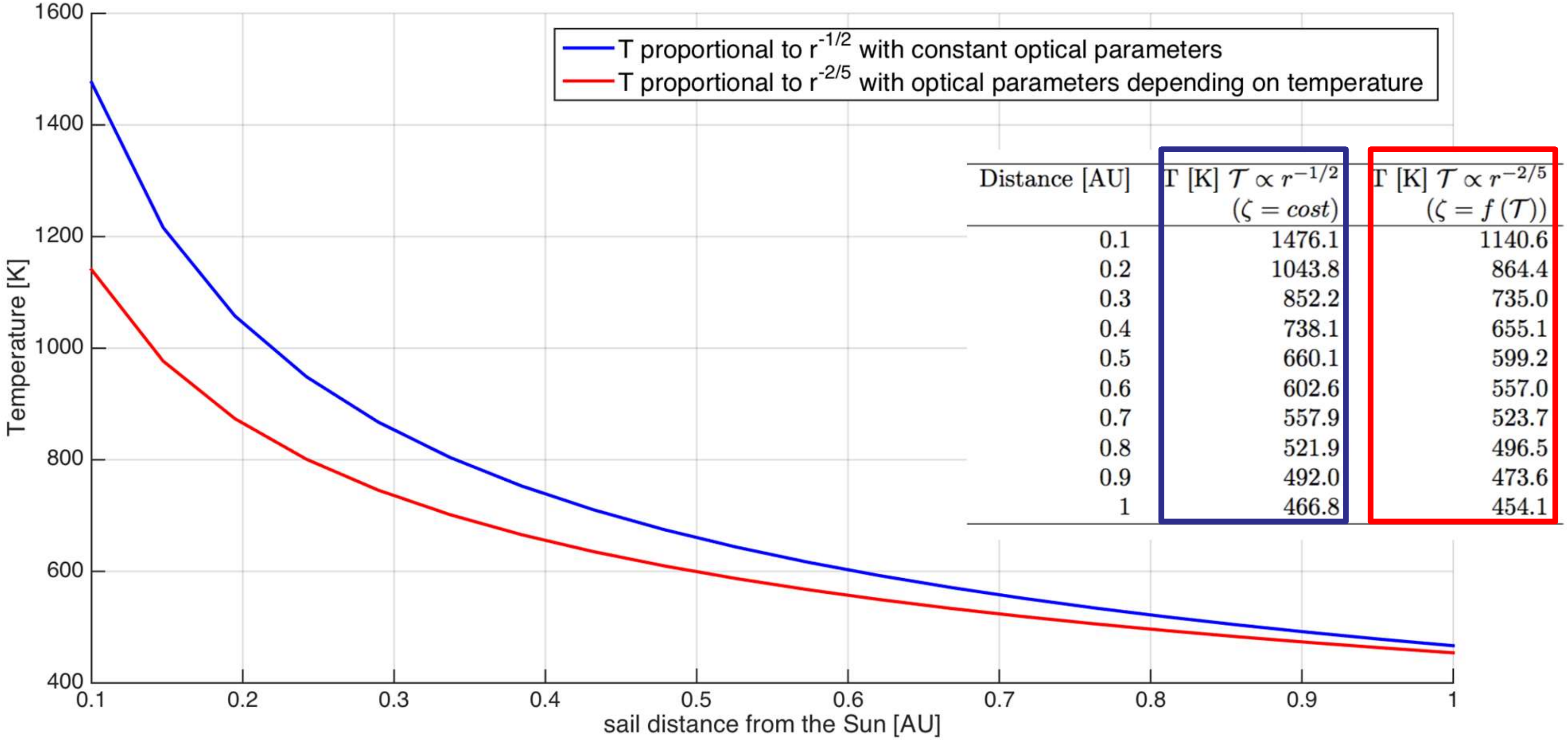
Thermal desorption: the propulsion mechanism

- The acceleration due to desorption is of the order of m/ s^2, whereas that of photon pressure is few mm/ s^2 ;
- With an approach so close to the Sun, we get velocity increment of hundreds of km/ s .



Temperature dependence on heliocentric distance

- Thermal desorption is effective and advantageous for high values of temperature.
- The temperature of a solar sail increases as $r^{-2/5}$ when the heliocentric distance *r* decreases because of temperature dependence of the emissivity and conductivity.



Distance [AU]	T [K] $\mathcal{T} \propto r^{-1/2}$ ($\zeta = cost$)	T [K] $\mathcal{T} \propto r^{-2/5}$ ($\zeta = f(\mathcal{T})$)
0.1	1476.1	1140.6
0.2	1043.8	864.4
0.3	852.2	735.0
0.4	738.1	655.1
0.5	660.1	599.2
0.6	602.6	557.0
0.7	557.9	523.7
0.8	521.9	496.5
0.9	492.0	473.6
1	466.8	454.1

Solar sailing

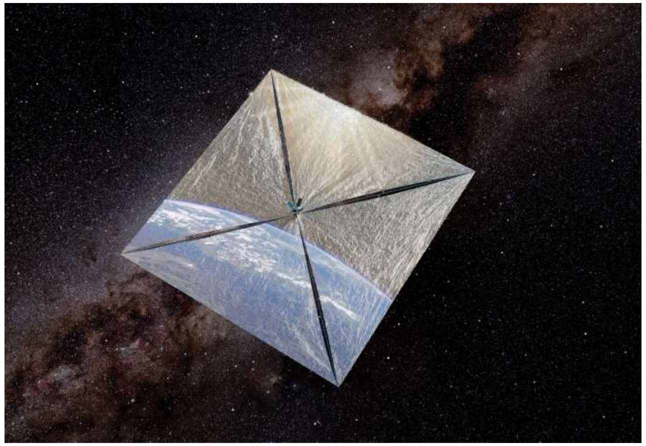
- "*tremendous **mirrors of very thin sheets***" (F. Tsander, 1924).

- large sheets of **low areal density** material (Kapton, Mylar) whose **only source of energy is the Sun photons flux**.

- **unlimited duration** (in theory) thanks to the "ever-present push of sunlight";

- **no propellant** is needed;

- **acceleration is slow but continuous**.



Solar sailing

- **Force due to solar radiation pressure** acting on the sail is function of its **reflectivity** and the solar irradiance (energy flux coming from the Sun) at a particular distance (c is the speed of light).

$$P_{sail} = \frac{1+\varrho}{c}\phi.$$

- Acceleration of the sail:

$$a = \frac{P_{sail} \cdot A \cdot cos^2\vartheta}{m} = \frac{1+\varrho}{c}\phi\frac{1}{\sigma} \cdot cos^2\vartheta = 3,04 \cdot 10^{25}\frac{1+\varrho}{\sigma \cdot c \cdot r^2} \cdot cos^2\vartheta$$

- **Sail loading factor**:

$$\sigma_s = \frac{m_s}{A} \left[\frac{g}{m^2}\right]$$

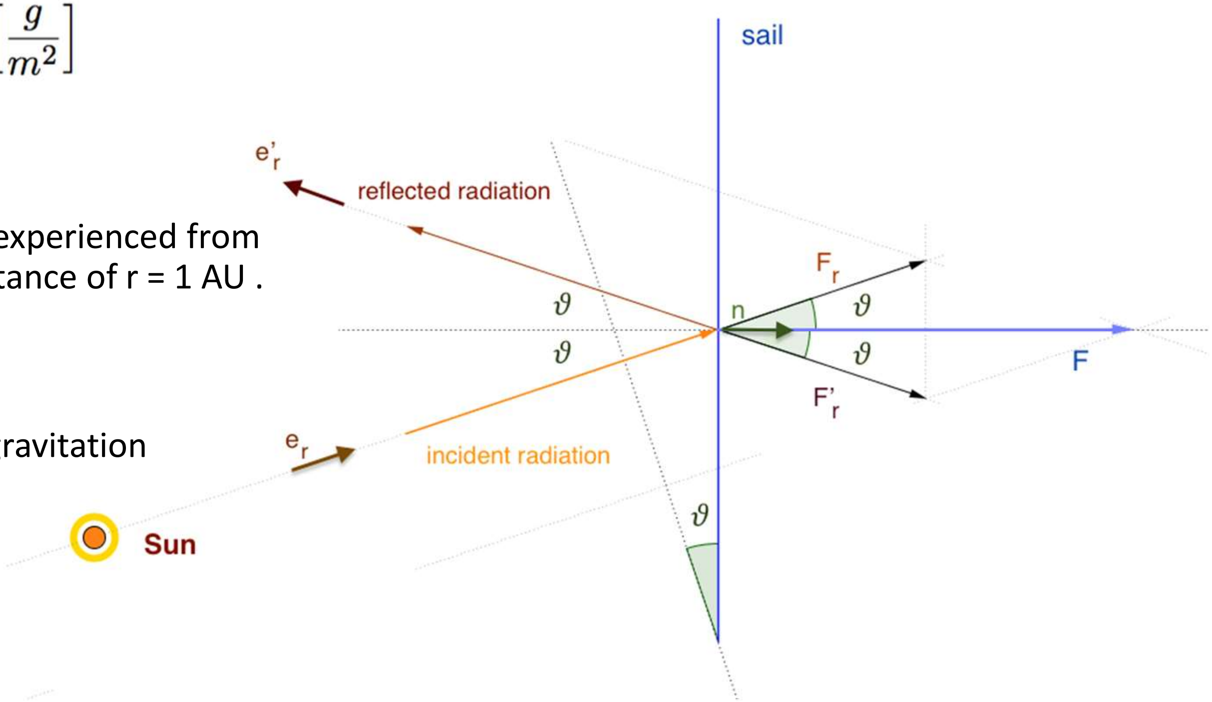
- **Characteristic acceleration**:

  maximum acceleration that can be experienced from the sail if normal to the Sun at a distance of r = 1 AU .

- **Lightness number**:

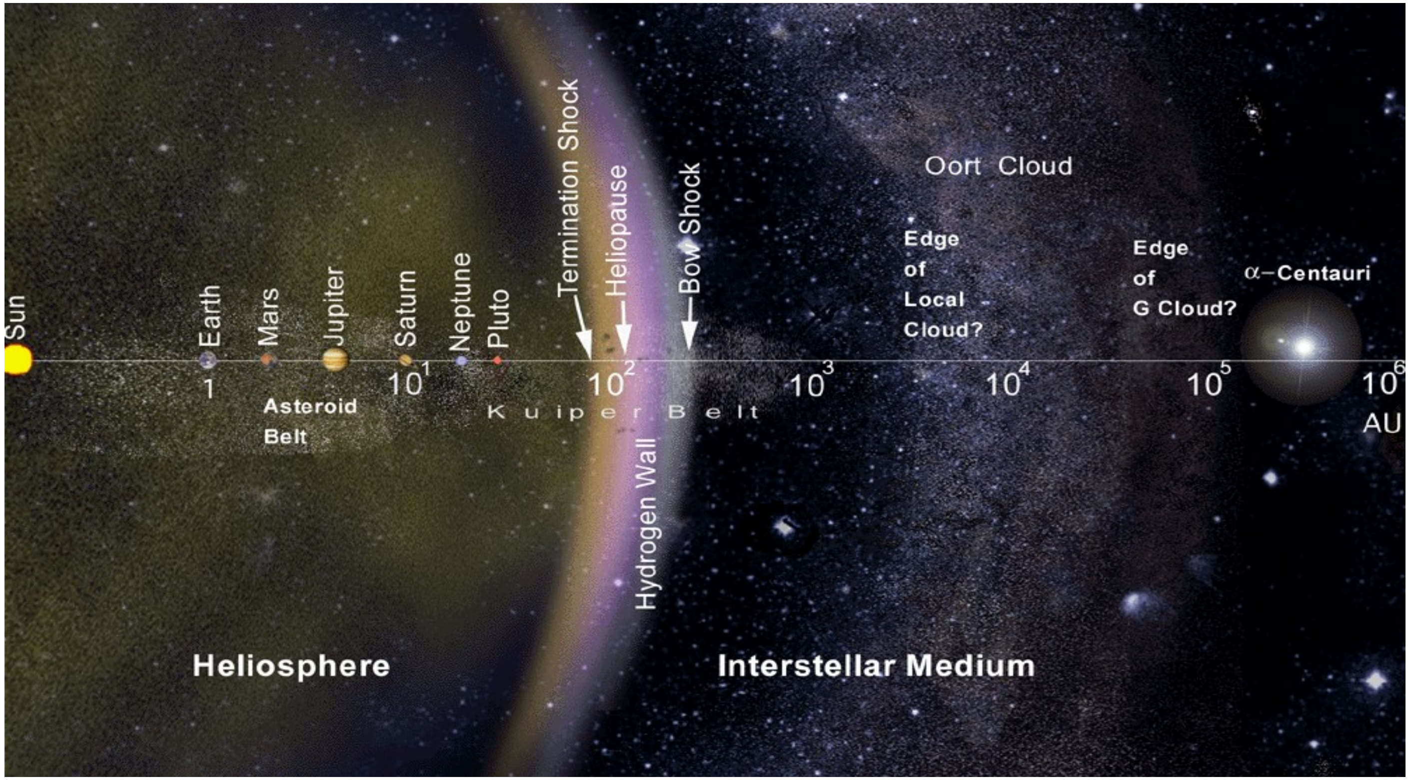
  solar radiation pressure over solar gravitation at same distance.

$$\beta = \frac{a_0}{(g)_{1AU}} = \frac{a_0}{5.93\ mm/s^2}$$



Why Sedna?

Missions to the Kuiper Belt region and beyond, the Oort Cloud, the gravitational focus of the Sun, and even the Alpha-Centauri system are considered the next breakthrough for space exploration. Among various suggested destinations, the trans-Neptunian object Sedna (90377) has recently gained more and more interest from the scientific community.



Why Sedna?

- Sedna, orbiting the Sun in a highly eccentric orbit, is currently on the way to its perihelion (around **76 AU** from the Sun), and recent studies consider this an extraordinary opportunity to get to know more about deep space, being its aphelion at about **936 AU**.

- Given the **orbital period of 11 thousand years**, scientists have been proposing missions for launch in the next few years (around 2030), including gravity assist that would allow to reach Sedna in time for its closest approach [***V.A. Zubko, A.A. Sukhanov, K.S. Fedyaev, V.V. Koryanov, A.A. Belyaev, "Analysis of mission opportunities to Sedna in 2029–2034", Advances in Space Research, 68, 2752-2775 (2021)***]

Proposed scenarios

- Solar sail coated with materials that undergo thermal desorption at a particular temperature, as a result of heating by solar radiation at a particular heliocentric distance.

- Three different scenarios for extra-solar space exploration with a solar sail:

- **1st scenario: Hohmann transfer plus thermal desorption acceleration.**

  Hohmann transfer from Earth's orbit to an orbit very close to the Sun (almost at 0.1 AU) with chemical propulsion.

  Sail deployed and the coat undergoes desorption at the temperature reached at the perihelion of the transfer orbit.

  The sail escapes the Solar System having in addition the conventional acceleration caused by solar radiation pressure.

- **2nd scenario: Elliptical transfer plus Slingshot plus thermal desorption acceleration.**

  Generic transfer from Earth to Jupiter and Jupiter's fly-by leads to the orbit close to the Sun.

  Then the sail is deployed and continues as in 1st scenario.

- **3rd scenario: Two stage acceleration of the solar sail through thermal desorption.**

  The sail has two coats of the materials that undergo thermal desorption at different solar sail temperatures depending on the heliocentric distance.

  First desorption at the Earth orbit leads the sail toward the Sun (spiral trajectory).

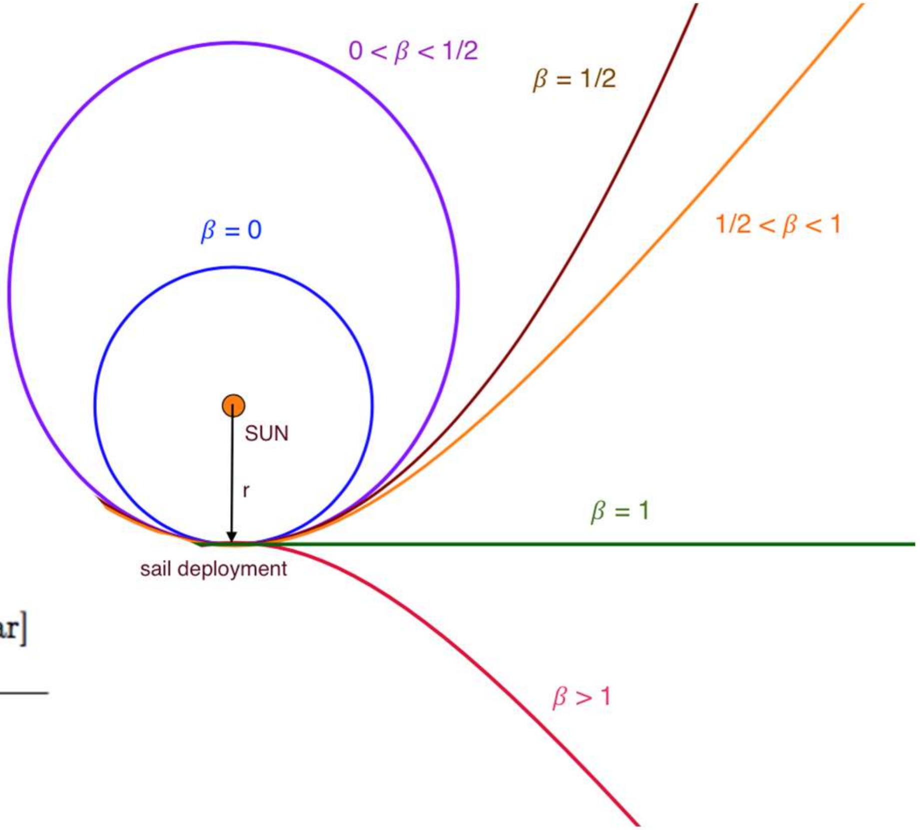
  Second desorption as in the other scenarios.

After desorption: sail cruise speed

Once desorption has occurred at perihelion, one can evaluate what the cruise speed of the sail will be with the law of energy conservation.

$$E_g = \frac{v^2}{2} - \frac{\mu(1-\beta)}{r} = \frac{v_P^2}{2} - \frac{\mu(1-\beta)}{r_P}$$

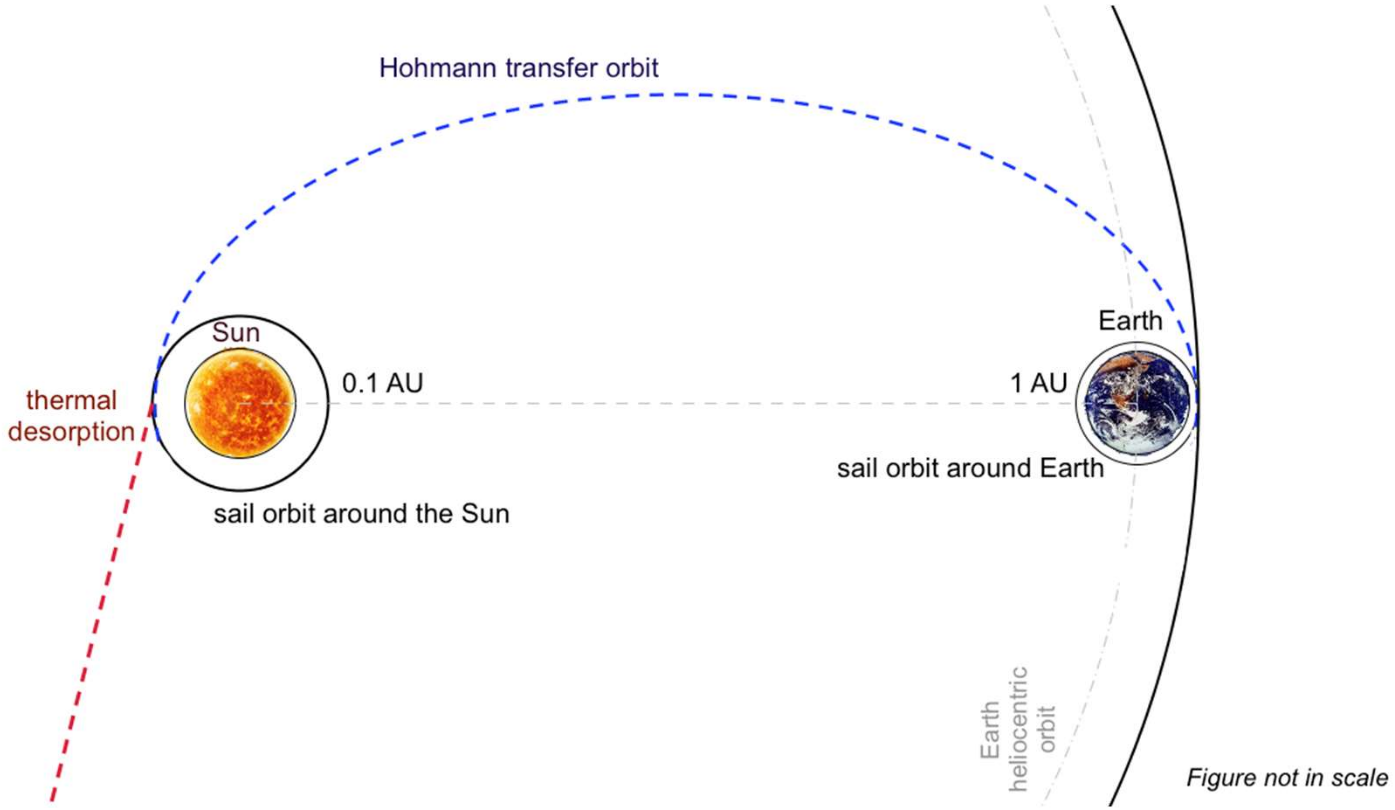
Orbital mechanics of solar sail depends on sail lightness number: in order to escape $\beta>1/2$ is required.



σ $[g/m^2]$	β	v_{cruise} [km/s]	distance/year [AU/year]
2.5	0.5	86.7	18.3
2.1	0.6	95.6	20.2
1.7	0.7	106.9	22.6
1.4	0.9	122.5	25.8
1	1.2	145.7	30.7

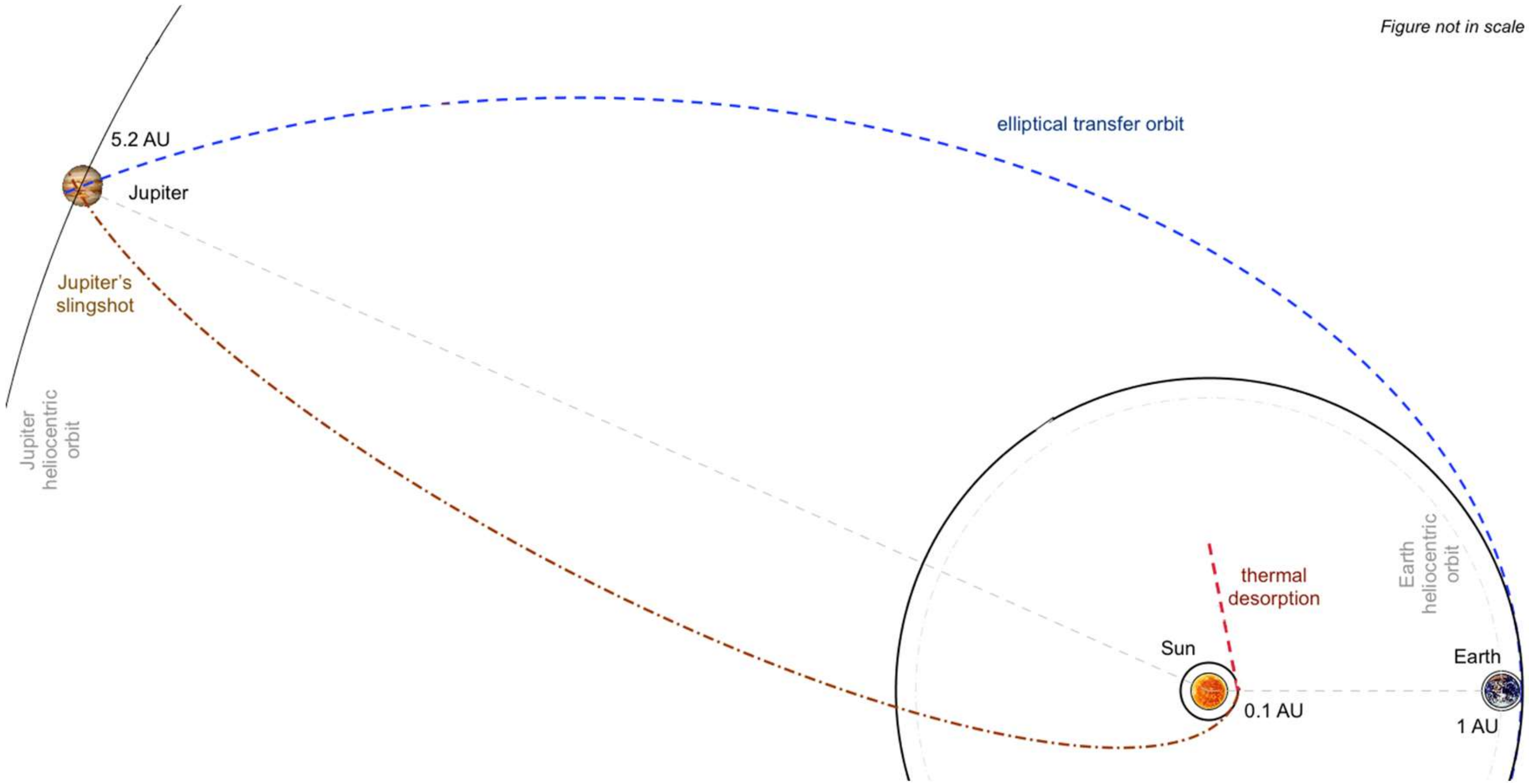
1st scenario: Hohmann transfer plus thermal desorption acceleration

- Hohmann transfer from Earth's orbit to an orbit very close to the Sun (almost at 0.1 AU) with a conventional chemical propulsion.
- The sail is deployed at the perihelion.
- It has one coat of the material that undergo desorption at the temperature reached at the perihelion of the transfer orbit.
- The sail then escapes the Solar System thanks to the conventional acceleration caused by the solar radiation pressure.



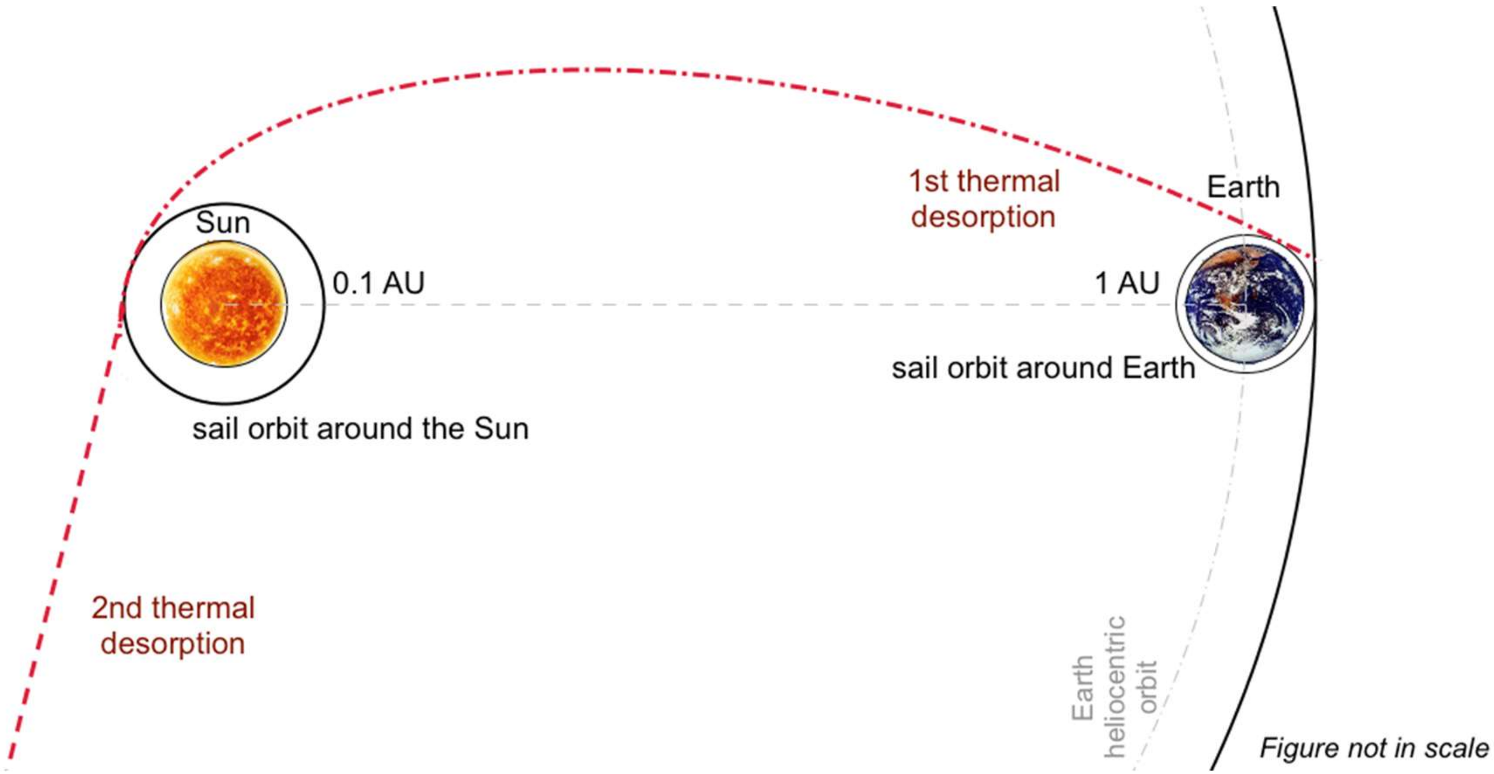
2nd scenario: Elliptical transfer plus Slingshot plus thermal desorption

- The transfer occurs from Earth's orbit to Jupiter's orbit.
- A Jupiter's fly-by leads to the orbit close to the Sun.
- Then as in first scenario:
    - The sail is deployed at the perihelion.
    - It has one coat of the material that undergo desorption at the temperature reached at the perihelion of the transfer orbit.
    - The sail then escapes the Solar System thanks to the conventional acceleration caused by the solar radiation pressure.



3rd scenario: Two stage acceleration of sail through thermal desorption

- The sail has two coats of materials that undergo thermal desorption at different solar sail temperatures, that means at different heliocentric distances.
- The sail is deployed.
- The first desorption occurs at the Earth orbit and provides the thrust needed to propel the solar sail toward the Sun.
- Then as in first scenario:
  - The other coat undergoes desorption at the temperature reached at the perihelion of the transfer orbit.
  - The sail then escapes the Solar System thanks to the conventional acceleration caused by the solar radiation pressure.

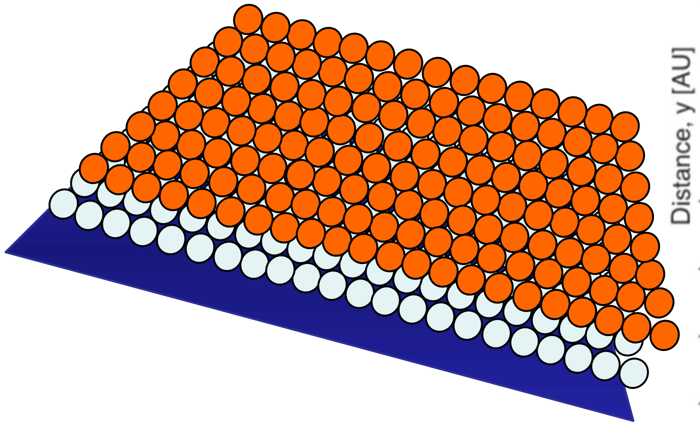


3rd scenario: Two stage acceleration of sail through thermal desorption

Sail deployed from the beginning: spiral logarithmic trajectory;

Two coatings that undergo desorption

- **β relative to the coat** that will desorb at perihelion (and not to the sail!);



- If β increases, the transfer would require **less time but higher DV**.

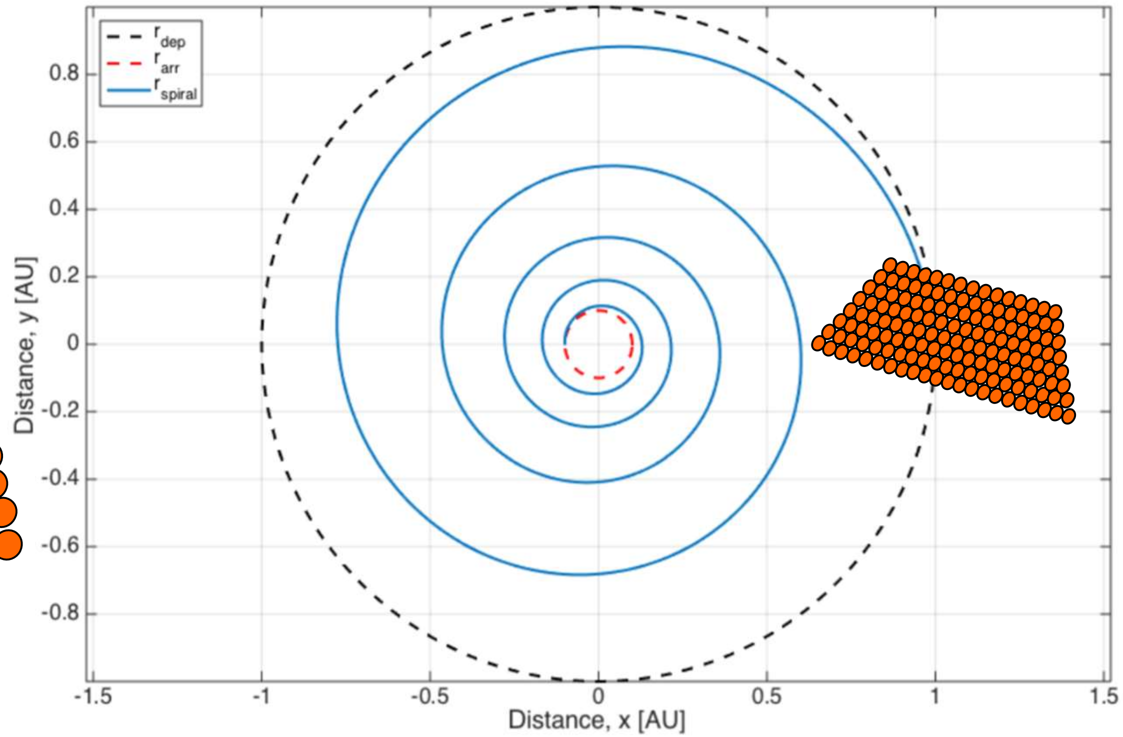


Figure 6.18: Solar sail trajectory from 1 AU to 0.1 AU with optimum pitch angle $\vartheta = 35°$ and low lightness number $\beta = 0.1$. The outer black circle of radius r_{dep} and the inner red circle of radius r_{arr} represent the departure and arrival orbits, respectively.

Comparison: 1st and 2nd scenario

- 1st scenario always convenient from a time point of view (only 73 days vs 558 days[1])…
- …but as the heliocentric distance to reach decreases, its cost gets very high.
- The Jupiter flyby allows to reach 0.1 AU with an acceptable fuel cost.
- Depending on the material, the scenario which guarantees the best performance can be considered.

			Hohmann transfer from Earth			Jupiter Flyby		
radius desorption	r_P_des	[AU]	0,3	0,2	0,1	0,3	0,2	0,1
temperature	T	[K]	737	865	1140	737	865	1140
time of flight	t_f	[years]	0,26	0,23	0,20	1,73	1,63	1,53
speed at r1 (des)	v1	[km/s]	67,39	85,91	126,89	73,24	91,28	129,11
delta V required	ΔV_0	[km/s]	6,79	8,93	12,53	6,72	6,86	7,05

[1]only to get to Jupiter

Scenarios comparison

Scenario	**1**		**H + TD**		
Perihelion	r_P	$[AU]$	0.3	0.2	0.1
Speed at r_P before desorption	v_{arr}	$[km/s]$	67.39	85.91	126.89
Speed at r_P after desorption	v_P	$[km/s]$	167.16	213.43	315.81
Cruise speed	v_{cruise}	$[km/s]$	170.65	217.54	321.43
Distance/year	AU_y	$[AU/year]$	35.9	45.8	67.7

2		**E + GA + TD**		
r_P	$[AU]$	0.3	0.2	0.1
v_{arr}	$[km/s]$	73.24	91.28	129.11
v_P	$[km/s]$	181.82	226.90	321.44
v_{cruise}	$[km/s]$	185.04	230.76	326.90
AU_y	$[AU/year]$	39.0	48.7	68.9

Remember Sedna rP: 76 AU

Our choice: 2nd scenario

Scenario	**3**		**TD + Sail + TD**		
Perihelion	r_P	$[AU]$	0.3	0.2	0.1
Time required	t_f	$[days]$	409	445	474
Speed at r_P before desorption	v_{arr}	$[km/s]$	54.33	64.77	91.60
Speed at r_P after desorption	v_P	$[km/s]$	134.42	160.44	227.41
Cruise speed	v_{cruise}	$[km/s]$	138.74	165.87	235.07
Distance/year	AU_y	$[AU/year]$	29.2	34.9	49.5

- best cruise speed and distance covered in time!
- Also less DV than 1st scenario (7 instead of 12 km/s) thanks to the fly-by maneuver.
- … but more time required!

However, 3rd scenario could be a good way to reduce time and DV required

Conclusions and future developments

- We recommend using a solar sail that takes advantage of thermal desorption of its coating as an additional propulsion mechanism, beside its conventional acceleration.
- Thermal desorption can provide supplementary thrust as heating liberates atoms, embedded on the surface of the solar sail.
- To enhance this feature, the solar sail would first get closer to the Sun, and only then be deployed.
- The heliocentric distance to target would be given by the desorption temperature of coating materials' properties. As a result of heating by solar radiation at the specific heliocentric distance, the sail would benefit from a further thrust component.
- During the process of the thermal desorption one can neglect the acceleration due to solar radiation because this acceleration is an order of magnitude less than the one due to thermal desorption.
- We considered a perihelion of 0.3 AU and the desorption effects on the cruise speed of the solar sail. Application of this technology with state-of-the-art sails can result in solar-system exit velocities in excess of 100 km/s, as mentioned in previous studies targeting Kuiper Belt Objects.
- Future developments: mission specific evaluation for the desired scenario.

Questions?

Thank you for your attention