71st International Astronautical Congress 2020

The Interstellar Report - Part 1 of 2

This year's Congress was a ***Cyberspace Edition*** offered without registration fee, free of charge for a global community. Principium readers, and especially i4is members could therefore access the whole programme. This was a possibly unique opportunity to engage with this global event without the substantial entry fee normally charged and, of course, without travel expenses.

The catalogue of all technical sessions is at -

iafastro.directory/iac/browse/IAC-20/catalog-technical-programme

In this report and in part two in our next issue we aim to report all the items likely to be of special interest to Principium readers. Many were explicitly interstellar in topic but others are important in contributing to our interstellar goal including innovations in propulsion, exploitation of resources in space, deep space communication and control, enhanced and more economical access to space, etc.

Our reporters are -

- Dr Al Jackson (AJ)
- Angelo Genovese (AG)
- Adam Hibberd (AH)
- Olivia Borgue (OB)

- Our thanks to all of them. We also have reports from John Davies (JID)

On this occasion access to both papers and presentations has been granted, to all who register by the International Astronautical Federation (IAF).

Registration is available at -

https://iac2020.vfairs.com/en/registration

However we have also sought out open publication without registration and cited links where we have found them.

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IAC-20,C4,9,7,x56172	Exploration of trans-Neptunian objects using the Direct FusionDrive	Mr. Paolo Aime	Politecnico di Torino	Italy

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/manuscripts/IAC-20,C4,9,7,x56172.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/presentations/IAC-20,C4,9,7,x56172.show.avi

Open paper: https://webthesis.biblio.polito.it/14755/

Reported by: Olivia Borgue

The study presents exploration possibilities enabled by a direct fusion drive (DFD) nuclear propulsion system [1]. The DFD is half-way between a conventional NTP and an electromagnetic thruster. The propellant is deuterium plasma heated by fusion products, magnetic fields contain and heat up the fuel. The expected performance is illustrated in Figure 1.

	Low power		High power		Our choice
Fusion power, [MW]	1		10		2
Specific impulse, [s]	8500	8000	12000	9900	10000
Thrust, [N]	4	5	35	55	8
Thrust power, [MW]	0.46		5.6		1
Specific power, [kW/kg]	0.75		1.25		1

Figure 1. Expected performance of direct fusion drives (from Aime, Table 1)

The targets addressed in this study are trans-Neptunian objects (TNOs) such as Pluto, Eris, Haumea or Makemake. More specifically, they targeted Haumea with the objective of delivering at least 1500 kg of payload within 10 years of flight, maintaining a constant engine performance.

The trajectory is designed to have a spiral departure phase, an interplanetary phase and a rendezvous phase (Figure 2). The thrust of the DFD is expected to be comparable to that of the most efficient electromagnetic high-power thrusters, but the specific impulse would be higher.

They expect that the DFD will enable an entirely new class of interstellar missions.

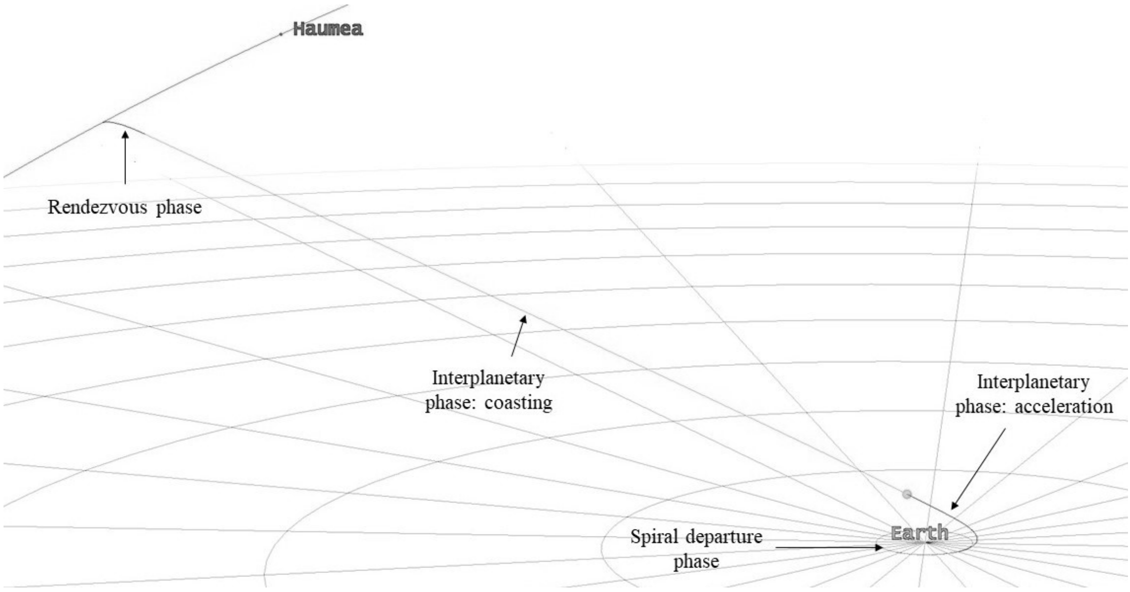


Figure 2. Trajectory to reach Haumea with a DFD (from Aime Figure 1)

[1] See also *A Titan mission using the Direct Fusion Drive* in *Interstellar News* in this issue.

IAC-20.C4.9.4	A High Inclination Solar Mission enabled by Near-Term Solar Sail Propulsion	Mr. Les Johnson	NASA, Marshall Space Flight Center	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/manuscripts/IAC-20,C4,9,4,x57111.pdf

IAF cited presentation video:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/C4/9/presentations/IAC-20,C4,9,4,x57111.show.mp4

Open paper: none found

Reported by: Olivia Borgue

Why study the sun from its poles (high inclination solar mission)? Because it provides information that we cannot obtain from other angles. It is like expecting to understand Earth weather without knowing what happens in the polar regions.

A high inclination solar mission would gather information about the Sun´s magnetic fields, solar winds and space weather. The problem is how to get to high inclination solar orbits and how to get the data.

Conventional alternatives to reach high orbits have many drawbacks:

- rockets are impractical,
- gravity assist maneuvers have very long period orbits and not much time is spent gathering data,
- electric propulsion takes a lot of mass and volume in propellant and would interfere with measurements.

The ideal solution is to use solar sails (photon pressure to produce thrust), they don´t require propellant and provide a large delta V. However, they are underdeveloped. Few missions have implemented solar sails (Figure 1). Nevertheless, other missions are currently ongoing or planned for the near future (Figure 2)

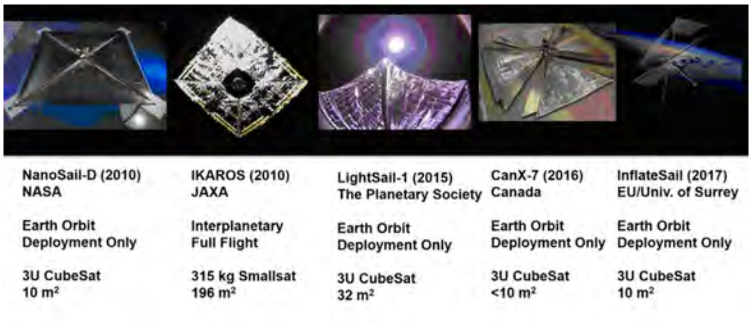
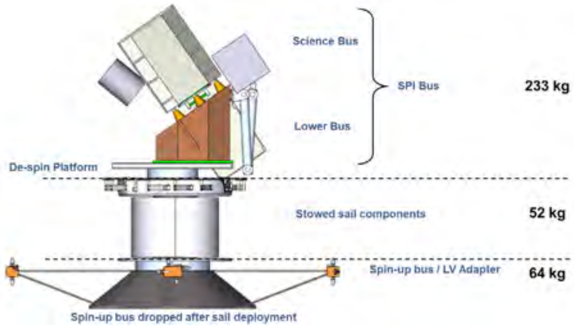


Figure 1. Missions that implemented solar sails.

Figure 2. Current and planned solar sails missions.



The HISM sailcraft mission concept showing the science bus and the separate, separable spin-up bus.

Credit: Johnson (Figure 2)

This study presents a solar sail based on a scaled Solar cruiser design, proposed to be launched by NASA in 2024. The solar sail in this study is scaled up to 7000 m^2 and would take science observation moving towards and from the target orbit. It aims at implementing remote sensing and in SITU science observation mission to study the suns behavior at high inclinations. It is estimated that the space craft can be built with existing capabilities with a total mission time of 9-12 years depending on the weight.

IAC-20,D4,4,2,x60132			
Rapid Access to the Interstellar Medium: A Feasibility Study	Dr. Leon Alkalai	NASA/JPL	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,2,x60132.pdf

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Open paper: None found

Reported by: Angelo Genovese & Adam Hibberd

Angelo Genovese

This paper is about the results of a JPL feasibility study on the rapid access to the interstellar space beyond the Solar System. Using current technologies (New Horizons) at least two centuries are required to reach the solar-gravity lens focus area (SGLF 550 AU). The goal of this study was to explore mission and flight system concepts that will reach the solar-lens focus in less than 50 years.

The launch system considered is the SLS Block 2B + EUS (Extended Upper Stage) + Advanced Boosters option as it offers the highest performance of this new heavy-lift expendable launch vehicle family.

The authors propose two different mission design philosophies: 1) low launch characteristic energy[1] C3 (~20 km^2/s^2) with a big launch mass (~38,000 kg) carrying a large amount of propellant to a solar perihelion point where a big burn (Oberth maneuver) would cause the spacecraft to have a fast solar system escape velocity, 2) very high C3 (~120 km^2/s^2) and a much smaller probe (~6,000 kg) performing just a Jupiter-powered flyby.

Two propulsion technologies are considered for the solar Oberth maneuver, namely Solar Thermal Propulsion (STP) and conventional Solid Rocket Motors (SRM). This study shows that SRM outperforms conventional STP, as can be seen in Table 2 (STPc Only vs SRM Only); the SRM final escape velocity is 12.4 AU/yr versus the STPc final escape velocity of 10.3 AU/yr.

Table 2 Mission Architectures Performance Comparison (credit: Alkalai/ JPL)

	50 AU (KBO's) (yr)	125 AU (ISM) (yr)	550AU (SGLF) (yr)	Final Vesc (AU/yr)	Mission
STPc Only	12.8	20.2	62.6	10.3	Solar
STPc NEP	13.3	20.1	51.6	13.6	Solar
STPi Only	11.0	15.5	41.2	16.6	Solar
STPi NEP	11 .4	16.1	38.5	19.5	Solar
SRM Only	12.0	18.1	52.7	12.4	Solar
SRM NEP	12.3	18.1	44.6	16.2	Solar
SRM Only	7.9	18.1	75.9	7.4	Jupiter
SRM NEP	8.8	16.9	55.5	11.0	Jupiter
NEP Only	10.7	20.6	53.5	14.2	Jupiter

Furthermore, even higher escape velocities can be reached combining a SRM or STP system with a low thrust propulsion system, as the new Nuclear Electric Propulsion (NEP) system developed by NASA's Glenn Research Center using the 10 kWe[2] Kilopower reactor and the NEXIS ion thruster.

The NEP system is utilized after the solar perihelion burn performed by either STP or SRM; for missions far deep in interstellar space (SGLF) NEP will show its performance, while for missions to closer Kuiper Belt Objects (KBO) having NEP is a sort of burden as NEP will add acceleration gradually to the spacecraft and it will take a long time for the spacecraft to reach high speed. So, if the goal is to reach KBO's fast using the first mission architecture, NEP should be absolutely off the table.

[1] https://en.wikipedia.org/wiki/Characteristic_energy

[2] kWe - kiloWatt electric - as distinct from the thermal power of the reactor

Figure 8 illustrates the above conclusions: the dark green (SRM ONLY) remains a rather flat line (constant escape velocity) for the entire mission, whereas the light green (SRM+NEP), although has a lower performance at the beginning, will pick up to a much higher escape velocity after 15 years from the solar perihelion. The escape velocities of both light and dark green become equal after about five years from the perihelion burn.

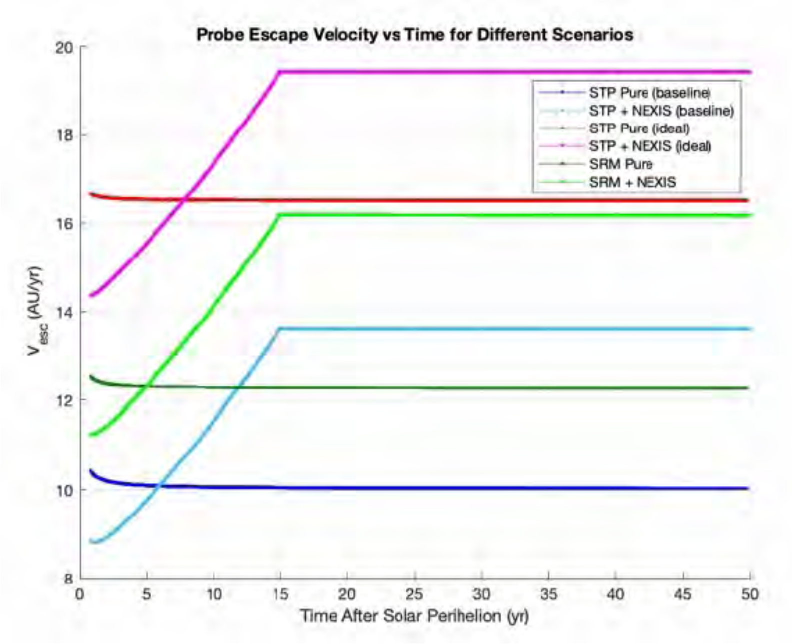

Fig 8 The Effect of NEP on Escape Velocity
Credit: Alkalai / JPL

The main drawbacks of the first mission design architecture are the technical thermal issues that result in a very high dry-mass/wet-mass ratio. An alternative mission architecture eliminates the need for a solar perihelion dive using a Jupiter powered flyby at low altitude (3,000 km). In this new scenario, the spacecraft is launched with a very high C3 (120 km^2/s^2) directly from Earth to a Jupiter powered flyby. Table 2 shows that for short distances (reach a KBO), a Jupiter-powered flyby seems appropriate; for distances to the ISM, a Jupiter-powered flyby followed by a NEP system could provide a good enough solution; and to reach far towards the solar-gravity lens focus and beyond, an SRM at solar perihelion followed by NEP seems to be the best option with an escape velocity of 16.2 AU/yr (4.5 times faster than Voyager 1).

If the technology of the STP system is further improved, the study shows that it can outperform an SRM due to its higher ISP (1350s). With a fully developed STP technology, an escape velocity of 19.5 AU/yr (5.4 times faster than Voyager 1) seems within reach. This could allow reaching the solar-gravity lens focus at 550 AU in less than 40 years; therefore, it is important to have continued investments into STP technology.

Adam Hibberd

In 2013/2014 the KISS study into rapid spacecraft missions to the Interstellar Medium was instigated as a result of firstly Voyager 1 detecting the Heliopause and secondly the detection by the Kepler Space Telescope of exoplanets. Two main ways of doing this, using current or near-future propulsion schemes were found to be:

1) travel to Jupiter followed by a Jupiter Oberth,

2) travel to Jupiter, then a passage close to the Sun and a Solar Oberth.

The research undertaken simulates using solar thermal propulsion for (2) exploiting the solar flux from the Sun and a heat-exchanger to vaporise propellant, in this case LH2. An Isp of approximately 1350s is achievable. The research found a 3 stage system for the Solar Oberth was a good solution. This could be installed into a SLS Block 2B.

As far as perihelion distance from the Sun is concerned it was found that there is a sweet spot at around 3 Solar Radii. Thus the closer to the Sun and the mass of the heat shield becomes too great, whereas further away the effectiveness of the SO reduces. Also currently, STP is not as good as Solid Rocket Motors (SRM) because an SRM has a comparatively low dry to wet mass ratio which gives a greater velocity increment (from the Tsiolkovsky equation). This may change with future development of STP.

Also low thrust Nuclear Electric Propulsion (NEXIS, 10 kW, Isp=7000s) was considered for the outbound phase after the Solar Oberth (1) or Jupiter Oberth (2). This is mainly worthwhile (in terms of high heliocentric excess velocities) for missions deep into the ISM (like to the solar gravity lens distance of 550 AU), rather than for example KBO (Kuiper Belt Objects).

Authors: Leon Alkalai, Reza R Karimi, Jonathan Sauder, Michael Preudhomme, Juergen Mueller, Dean Cheikh, Eric Sunada, Abby Couto, Nitin Arora, and Jacqueline Rapinchuk IAC-20,D4,4,6,x61030

IAC-20,D4,4,6,x61030	Feasibility assessment of deceleration technologies for interstellar probes	Mr. Kush Kumar Sharma	International Space University (ISU)	France

IAF cited paper:

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Open paper: None found

Reported by: Al Jackson & Adam Hibberd

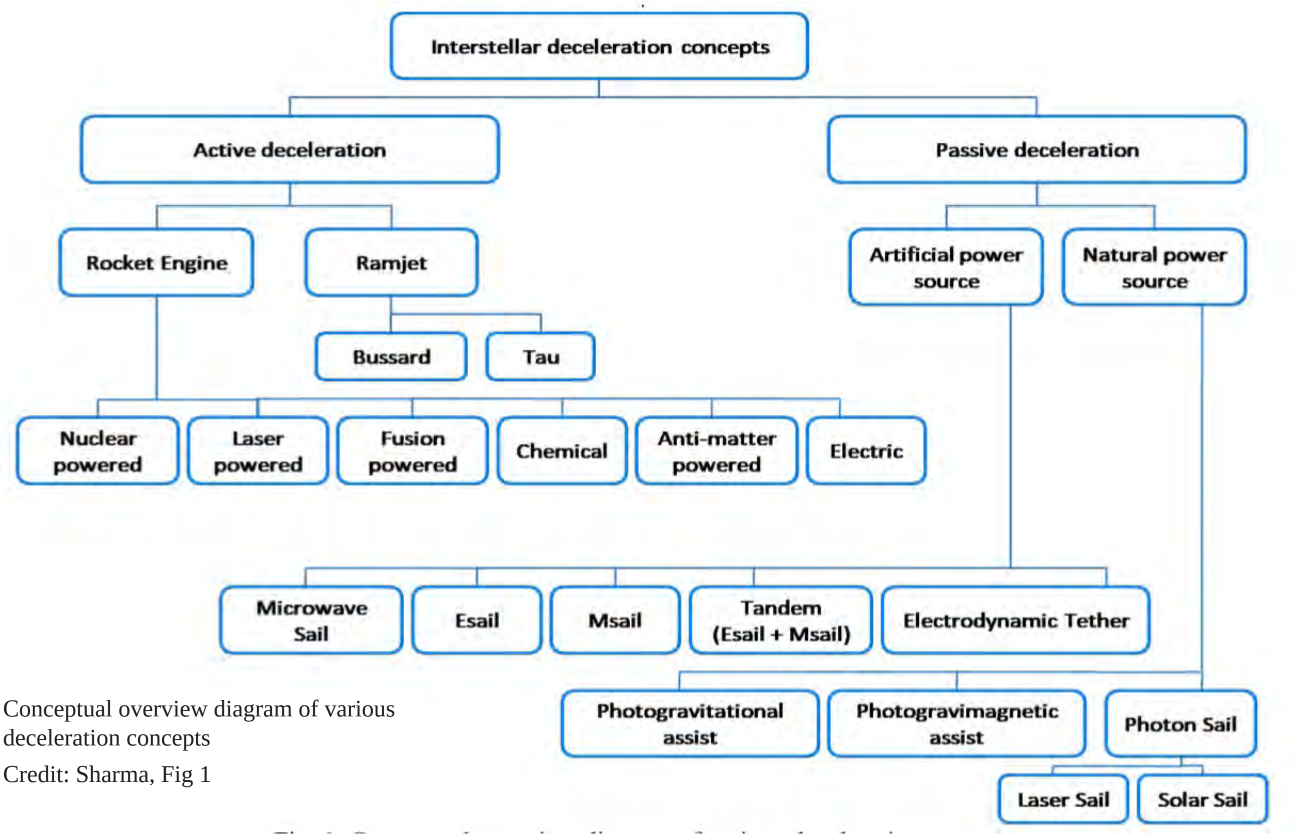
Al Jackson

An important element of interstellar flight is slowing or stopping at target destination. Massive spacecraft would require active deceleration mechanisms; lightweight spacecraft can use passive processes. This paper examines many in the chart given below. Active deceleration of a massive ship requires very large amounts of reaction mass or large power systems. Passive deceleration for small masses might use the medium, radiation or particles, near the target star. It may be possible to make use of the ‘stellar sphere’ of the target star to stop or slow down. Of interest is the interaction of an interceptor with the stellar sphere radiation forces and magnetic field of a target star. Of particular consideration is the interaction of a spacecraft with radiation pressure, Poynting-Robertson drag, Lorentz forces, stellar wind drag and Coulomb drag. A Technology Readiness Level assessment is made of the various systems that can be deployed.

Deceleration concepts	TRL
Electric sail	3 - 4
Magnetic sail	2 - 3
Tandem (esail + msail)	2
Solar sail	4 – 5
Photogravitational assist	2
Photogravimagnetic assist	2
Electrodynamic Tether	4

Technology Readiness Level assessment

Credit: Sharma Table 2:



Conceptual overview diagram of various deceleration concepts

Credit: Sharma, Fig 1

Adam Hibberd

Interstellar probe missions are high risk, high costs, but high scientific return. This return includes: Planetological + Astrobiological data, study of planets and satellites within the largest system, study of the Interstellar Medium. The nearest star is Alpha Centauri. An exoplanet, has been discovered around Alpha Proxima C, lying in the in the habitable zone. There are four mission types:

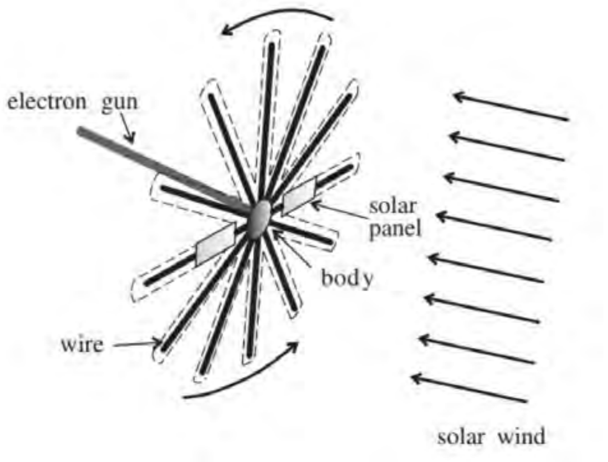
1) Flyby
2) Orbit Insertion
3) Landing (with or without rover)
4) Sample Return

The Mission phases are: acceleration, cruise, deceleration. There are two types of IS deceleration concepts, Active and Passive deceleration. Passive exploits natural astrophysical sources such as stellar radiation pressure, gravity, photons, interstellar ions, etc whereas active requires more mass in the form of fuel. Five passive deceleration schemes were assessed, Electric Sail, Magnetic Sail, Tandem Electric/Magnetic Sail, photogravitational assist, photogravimagnetic assist. The TR, Technical Readiness Level of all passive types are in the region 2-4, apart from the solar sail.

It was found that use of the tandem electric/magnetic sail reduced the deceleration time from 50 years for photogravitational assist to 28.8 years for tandem.

It was found that there is no common baseline which can be used to establish the relative efficacy of these different sorts of passive propulsion schemes. Recommendations are:

1) Develop mathematical model for using photogravimagnetic assist to decelerate a spacecraft.
2) Conduct preliminary design study with subsystem specifications for interstellar mission.
3) Explore the possibility of using laser- or microwave beamed energy derived from spacecraft's on board power for deceleration of small probes.
4) Study the effect of mass ejections of the star on the deceleration force and duration.
5) Perform a specific interstellar mission design study using the different deceleration concepts.
6) Explore potential deceleration methods by combining existing concepts.



Conceptual diagram of electric sail

Credit; Sharma, Fig 2

P. Janhunen, Electric Sail for Spacecraft Propulsion, Journal of Propulsion and Power , 20(4), 2004, 763-764.

space.fmi.fi/~pjanhune/Esail/paper1.pdf

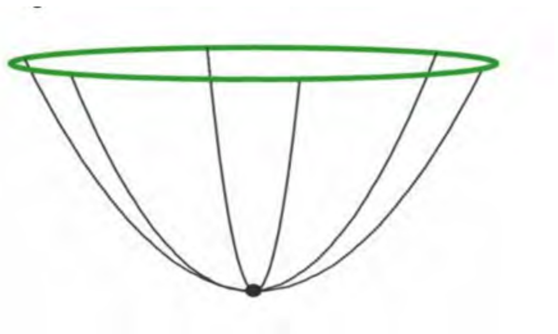


Illustration of magnetic sail in the form of superconducting Biot Savart loop (green)

Credit; Sharma, Fig 3

C. Gros, Universal scaling relation for magnetic sails: momentum braking in the limit of dilute interstellar media, Journal of Physics Communications (2018)

iopscience.iop.org/article/10.1088/2399-6528/aa927e/pdf

Authors: Kush Kumar Sharma, Prof Chris Welch (ISU), Dr Andreas Makoto Hein (Ecole Centrale de Paris and i4is)

IAC-20,D4,4,5,x58922			
Vaporization of interplanetary dust during the acceleration phase of a laser-driven lightsail	Ms. Monika Azmanska	McGill University	Canada

IAF cited paper:Mitigation of Interplanetary Media Impacts for Laser-Driven Interstellar Travel (new title)

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,5,x58922.pdf

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Open paper: None found

Reported by: Al Jackson

Light sails pushed by laser beams to velocities around 0.2 c have been proposed as propulsion systems for interstellar travel. These light sails will undergo high-energy collisions with small dust grains in the solar system environment. This paper proposes the plausibility of using the irradiance of the driver laser array to mitigate the damage to the sail during the acceleration phase of the mission. Displacement of dust via the laser light transmitted through the sail, as would be the case with thin dielectric sails, may be feasible. Charged particle re-direction via graded materials is an established technology that has been demonstrated experimentally in the particle accelerator community. The driver laser may have the ability to ablate the dust grains prior to impacting the sail. This study also concerned other grain materials (alumina, iron, etc) likely to be present in dust grains in the solar system. Issues of beam profile and laser interaction are addressed. There is some discussion of sail protection during the interstellar cruise phase.

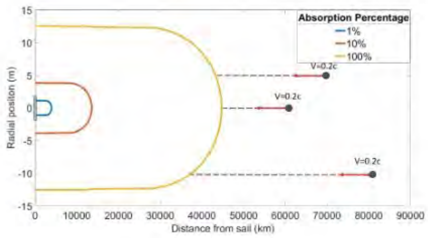

Fig. 1: a) Graphite Grain

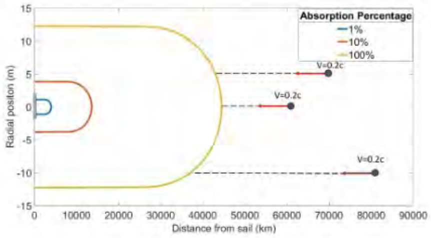

Fig. 2: b) Alumina Grain

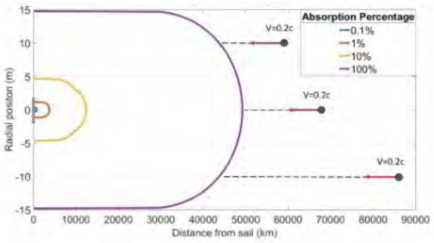

Fig. 3: c) Iron Grain

ablation analysis:

numerical results for the vaporization of dust grains travelling at 0.2c towards a lightsail positioned at 0.1 AU for a) graphite grain b) alumina grain c) iron grain

Credit (image and caption): Azmanska et al

Authors: John Kokkalis, Monika Azmanska, Andrew Higgins (all McGill University)

IAC-20,D4,4,4,x59255			
System Engineering a Solar Thermal Propulsion Mission Concept for Rapid Interstellar Medium Access	Dr. Jonathan Sauder	JPL-Caltech	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,4,x59255.pdf

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Open paper: None found

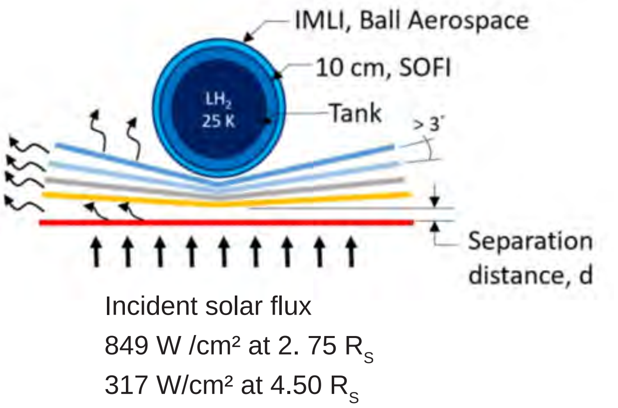
Reported by: Adam Hibberd

The goal is to gain access to ISM, six times faster than Voyager. In order to do this, two technologies were leveraged:

1) Solar Oberth Manoeuvre after travel to Jupiter, the E-J leg achieved by a combination of Earth/Venus gravity assists
2) Solar Thermal Propulsion to exploit the high solar flux close to the Sun

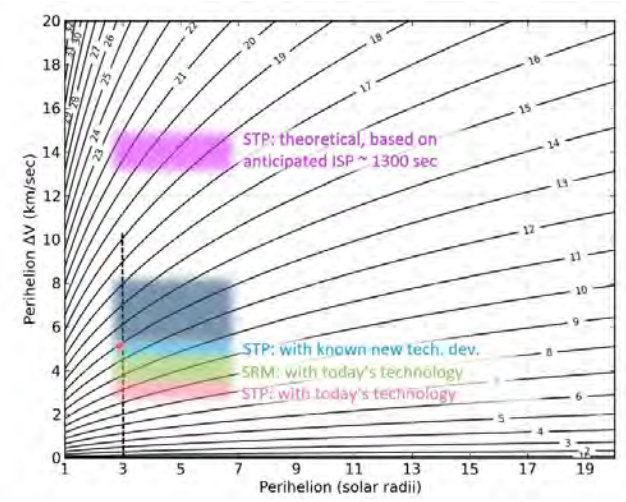
The spacecraft is assumed to use cryocoolers with LH2 propellant with a Barium Fluoride heat shield (size 17 m x 14 m) which is deployable so it can be stored in a SLS Block 2B Launcher. A numerical model for the spacecraft and the Solar Oberth was constructed with these assumptions and a Monte Carlo Simulation was performed. It was found that there is an optimal distance of the Solar Oberth of 3 Solar Radii, closer than this and the heat shield weight begins to detrimentally impact on the spacecraft's performance, further than this, the effectiveness of the SO reduces. Three stages were considered with optimal mass ratios 37:19:44.

Current Solid Rocket Booster (SRB) technology would allow Hyperbolic Excesses of 12 AU/yr whereas with Solar Thermal Propulsion, at its theoretical capability of Isp=1300s, 20 AU/yr can be achieved [1].



The heat shield assembly consists of a high-temperature panel exposed to the sun in addition to a set of radiation shields to further reduce the backloading onto the propellant tanks.

Credit(including captions): Sauder Fig. 4.



Performance of a Perihelion Oberth Maneuver

Credit: Sauder

Authors: Jonathan Sauder, Michael Preudhomme, Juergen Mueller, Dean Cheikh, Eric Sunada, Reza Karimi, Abby Couto, Nitin Arora, Jacqueline Rapinchuk, Leon Alkalai

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[1] 1 AU per year = 4.7 km/sec

IAC- 20,A3,4B,3,x56468			
Comet Interceptor: An ESA mission to a Dynamically New Solar System Object	Dr. Joan Pau Sanchez Cuartielles	Cranfield University	UK

IAF cited paper:

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iafastro.directory/iac/proceedings/IAC-20/IAC-20/A3/4B/presentations/IAC-20,A3,4B,3,x56468.show.mp4

Open paper: dspace.lib.cranfield.ac.uk/handle/1826/15881

Reported by: Adam Hibberd

Comet-I is the first f-class (fast class) mission by ESA, awarded in 2019 (www.cometinterceptor.space/). Other classes are l, s & m (large, small and medium). It will launch on an Ariane with the Ariel Exoplanet Telescope, both spacecraft being delivered to the Sun/Earth Lagrange 2 point. As far as budget, it has a €150M budget, equivalent to m-class.

The mission is to intercept a ‘dynamically new’ comet with surface ices laid down at the formation of the solar system, as opposed to those which have encountered the inner solar system many times with surfaces eroded as a result.

The comet must first be discovered by the Vera C Rubin Telescope. Current telescopes can pick comets up at distances between Jupiter and Saturn but there is the potential with the VCR to spot them much deeper in the Solar System, so much earlier, giving 2-3 years warning. The comet must have an intercept point reachable by the Comet-I stationed at its L2 point.

3000 long period comets have been discovered altogether, with 300 in the last 10 years. It has been calculated 21 of these would have had intercept points achievable by Comet-I. The sort of ΔV’s required are 0.5-2.0 km/s but with a Gravity Assist at Earth, this can be reduced to 0.1 km/s.

Comet-I consists of three craft, the mothercraft A which gets no nearer than 1000 km from the target comet whereas two subprobes B1 and B2 will get close and do the hard work [1].

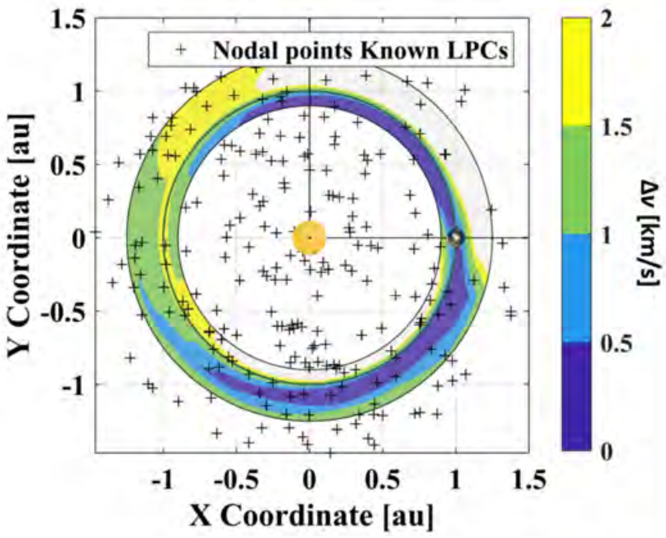
Summary of scientific instruments in Comet-I.

SPACECRAFT	INSTRUMENT	DESCRIPTION
ESA S/C A	CoCa	Visible Camera
	MANIaC	Mass Spectrometer
	MIRMIS	NIR/Thermal IR Imager
	DFP	Dust, Field & Plasma
ESA S/C B2	EnVisS	All-sky multispectral imager
	OPIC	Visible imager
	DFP	Dust, Field & Plasma
JAXA S/C B1	HI	Hydrogen Imager
	PS	Plasma Suite
	WAC & NAC	Wide and Narrow FOV cameras

Credit: Cuartielles et al, Table 1.

Accessible regions in the ecliptic plane as a function of different spacecraft’s Δv capabilities.

Credit (image and caption): Cuartielles et al Figure 4.



Authors: J P Sáncheza, G H Jones, C Snodgrass for the Comet Interceptor Science Team

[1] More about Comet-I in *News Feature: All Comets Great and Small*, Principium. Principium 25, May 2019 page 34. An account of the inaugural lecture delivered by Professor G H Jones at University College, London, 20 February 2019. Prof Jones is Mission Principal Investigator for this mission,

IAC-20,A5,4- D2.8,4,x58230			
Optimal Spacecraft Trajectories under Uncertainties	Mr. Deepak Gaur	Amity School of Engineering	India

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/IAC-20,A5,4-D2.8,4,x58230.pdf

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Open paper: None found

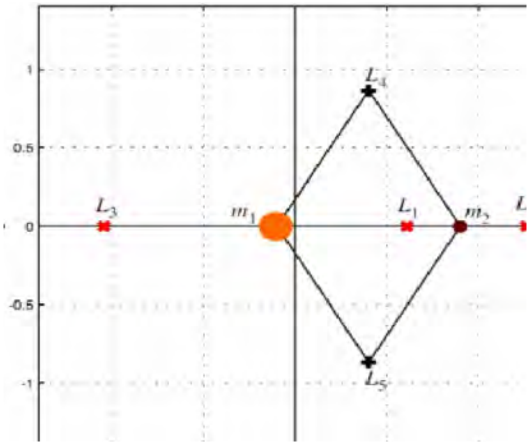
Reported by: Adam Hibberd

This paper was all about the Circular Restricted Three Body Problem (CRTBP) which is the scenario where there are two main bodies each orbiting in a circle around their common Centre of Gravity (these circles are coplanar) and a third object with zero or negligible mass. There is no known general solution to such a problem, however one constant of motion is known to be the Jacobi Constant, symbol 'C' as follows

$$C = 2U - V^2$$

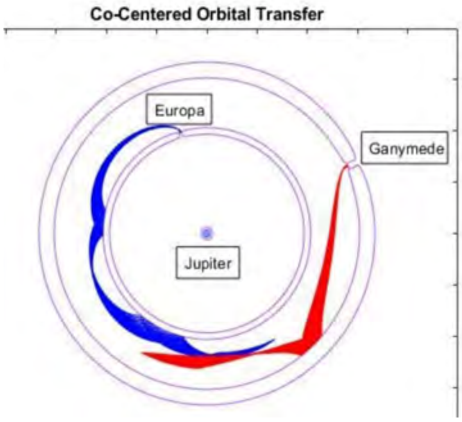
Where U is the potential and V is the speed. If we set $V=0$, ie find the trajectories which have zero velocity then we get $C = 2U$. This defines the ZVS (zero velocity surfaces) for different values of C. If we further set the gradient of the potential $\partial U/\partial x = \partial U/\partial y = \partial U/\partial z = 0$, this gives the particular values of (x, y, z) where the ZVS are stable, ie the Lagrange Points, L1, L2, L3, L4, L5. 3D Halo orbits are periodic orbits around Lagrange points. Other kinds of periodic orbit around Lagrange Points are Lyapunov orbits which have no z component and also vertical orbits.

Study of Low Energy Transfer (LET) orbit methodologies can be divided into 2 classes: Weak Stability Boundaries (WSB) & Dynamical Systems Theory (DST). WSB solutions tend to have long duration missions. The paper concentrates on DST.



Lagrange points for CRTBP[1]

Credit: Gaur Fig. 4.



Co-Centered Orbital transfer for Jupiter-Ganymede-Europa

Credit: Gaur Fig. 13.

Authors: Deepak Gaur, Mani Shankar Prasad

[1] Circular Restricted Three Body Problem.

Lagrange point typical cases -

System	m1(major mass)	m2(minor mass)	Example occupants of Lagrange point			
			L1	L2	L3	L4 and L5
Earth-Moon	Earth	Moon	possible station?	possible Moon farside relay	?	Kordylewski dust clouds
Sun-Earth	Sun	Earth	Solar and Heliospheric Observatory (SOHO)	ESA Gaia, NASA JWST	?	Unstable asteroids?
Sun-Jupiter	Sun	Jupiter	?	?	?	Trojan asteroids

IAC-20,D4,4,11,x58592	A Feasibility Analysis of Interstellar Ramjet Concepts	Ms. Taavishe Gupta	International Space University (ISU)	France

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/D4/4/manuscripts/IAC-20,D4,4,11,x58592.pdf

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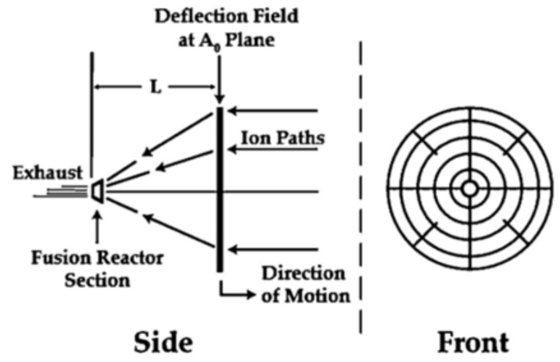
Open paper: None found

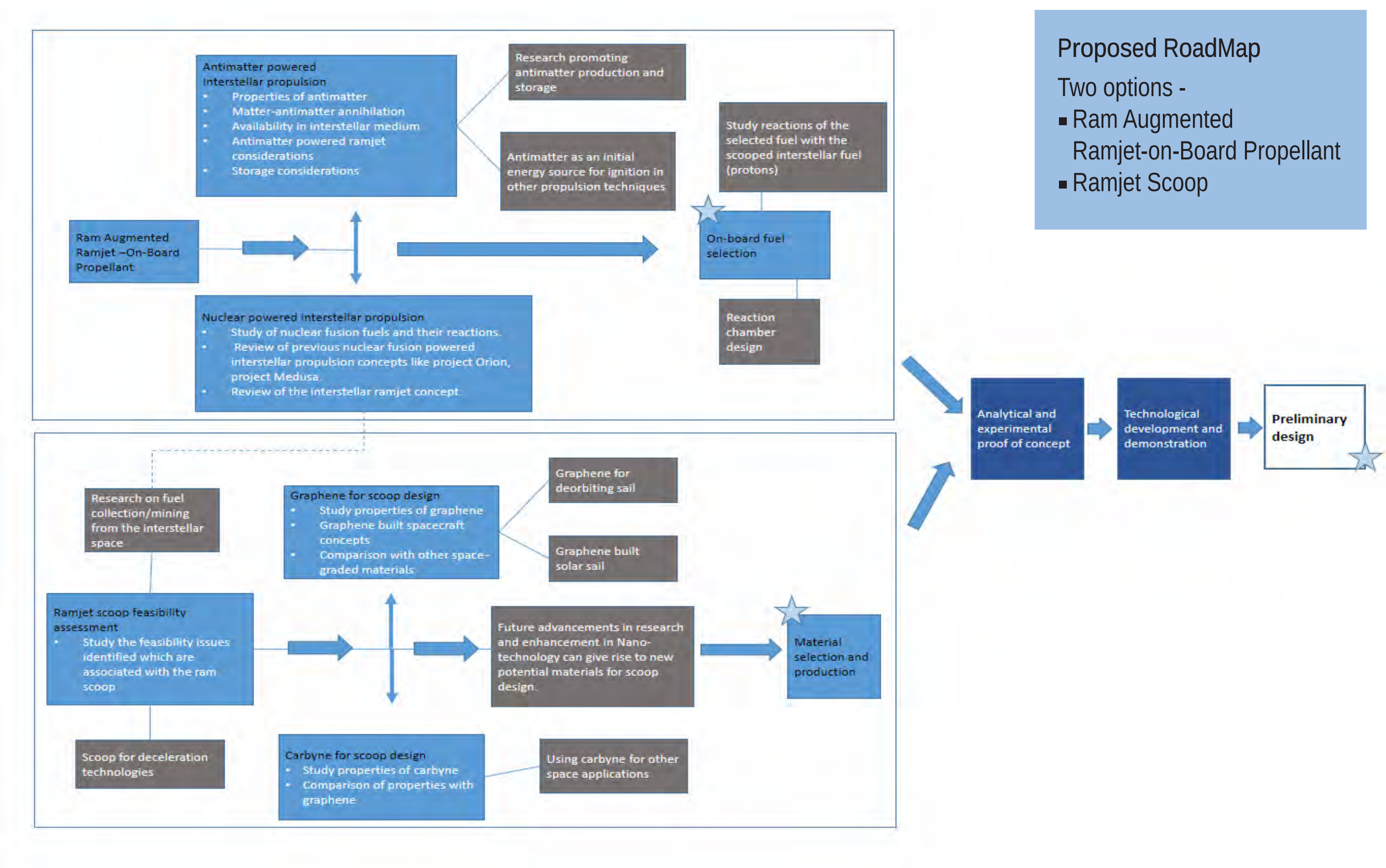
Reported by: Al Jackson

This paper is a comprehensive review of the interstellar ramjet. Robert Bussard's fundamental paper is reviewed. John Ford Fishback's extended analysis of the Bussard ramjet and Daniel Whitmire's solution to the difficult p-p fusion chain with the catalytic ramjet is covered. Variations on the interstellar ramjet are reviewed, the laser powered ramjet and the augmented ramjet. Conditions and properties of the interstellar medium are discussed. A feasibility study of interstellar ramjet concepts is outlined marking out areas of research, identifying capabilities and supporting technologies. A matrix of concept potential vs engineering physics is presented. A roadmap is presented with recommendations for further research. IAC-20,A5,4- D2.8,3,x59291

See also: *The Interstellar Ram Jet at 60*, A A Jackson, Principium | Issue 29 | May 2020 page 42



Schematic diagram of Bussard's ramjet concept
Credit: Gupta Fig. 2 [1]



Authors: Taavishe Guptaa, Andreas M Hein, Chris Welch

[1] Gupta refers to - B.W. Robert, Galactic Matter and Interstellar Flight, Astronautica Acta, Volume 6, 1960, (accessed 10.12.19).
The Bussard paper is available at - large.stanford.edu/courses/2013/ph241/micks1/docs/bussard.pdf

IAC-20,A5,4-D2.8,3,x59291			
Assessment of On-Orbit Cryogenic Refueling: Optimal Deport Orbits, Launch Vehicle Mass Savings, and Deep Space Mission Opportunities	Mr. Justin Clark	Ohio State University College of Engineering	USA

IAF cited paper:

iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/IAC-20,A5,4-D2.8,3,x59291.pdf

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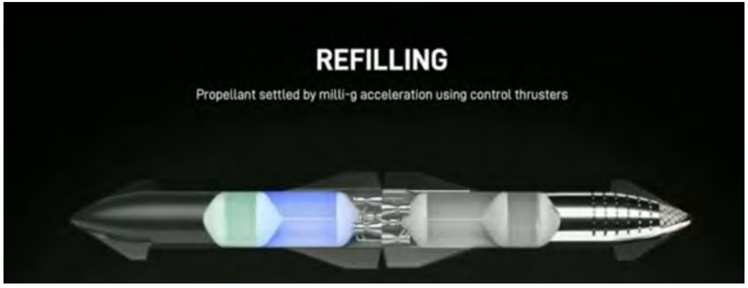
Open paper: None found

Reported by: John Davies

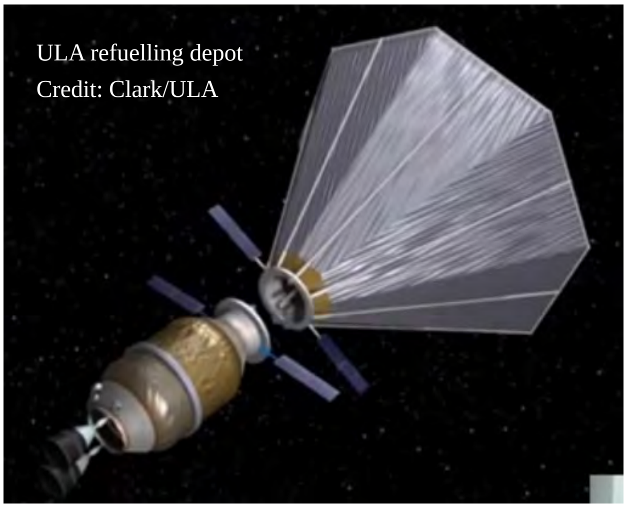
Mr Clark opened his justification for an orbital "gas station" (petrol station in UK) with an appeal to the Tsiolkovsky rocket equation, using the specific impulse formulation [1]-

$$\Delta V = g_0 * I_{sp} * \ln\left(\frac{m_0}{m_f}\right)$$

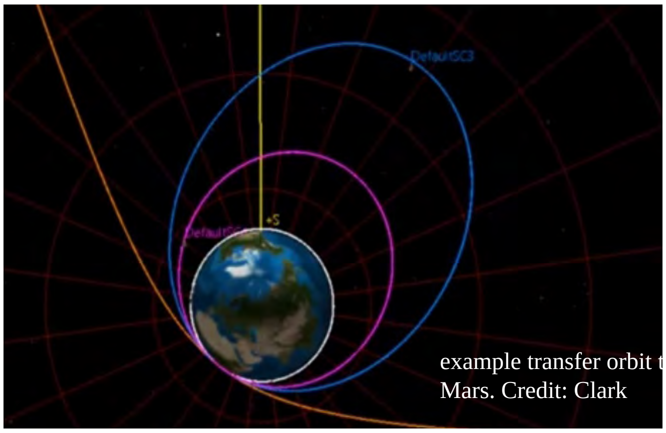
Proposals already exist for both - the ULA refuelling depot which is a semi-permanent depot [2] and the SpaceX "Starship" refuelling proposal.



SpaceX "Starship" refuelling proposal. Credit: Clark/SpaceX


ULA refuelling depot
Credit: Clark/ULA

Clark introduces some recent developments in technologies to enable refuelling including the NASA Robotic Refuelling Mission 3 (RRM3) to the ISS which demonstrated propellant transfer and a proposed 2023 NASA mission - a semi-permanent depot to explore techniques in transferring propellants (low-G transfer, vented chill & no-vent Fill) and to mitigate boil-off (insulation, cryocoolers). The Ohio State team have a method of optimising the orbit at which refuelling takes place. These allow missions to visit a refuelling station with no DeltaV penalty - these are gas stations on the freeway! They look at all elliptical orbits between an initial low earth orbit (LEO) and the target orbit for the mission, An example is a hyperbolic transfer orbit to Mars. Here the white initial orbit, two possible ellipses and the final Mars transfer orbit shown in orange. The method takes a destination, rocket stage mass ratios, and specific impulses and produces comparisons between optimal refuelling mission masses and a no-refuelling scenario with just one vehicle. The team modelled several scenarios varying launch vehicle stage specific impulses and mass ratios, one vs two stage launch vehicles and utilization of both lunar refuelling with locally produced fuels and of Orbital Transfer Vehicles (OTVs) with electric propulsion. Some examples studied included the NASA Artemis 1 to the Moon (with mass improvement factors around 2), the SpaceX Mars mission (with a wide range of results)



example transfer orbit t
Mars. Credit: Clark

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[1] Exhaust velocity, ve=g_o*I_{sp} hence the substitution, Quick dimensional analysis check g_o is the acceleration due to gravity so the dimensions are velocity=acceleration*time so m/sec = m/sec^2*sec = m/sec

[2] example www.ulalaunch.com/docs/default-source/exploration/evolving-to-a-depot-based-space-transportation-architecture.pdf

IAC-20,A5,4-D2.8,9,x59363	Nuclear Thermal Propulsion (NTP) Post-Burn Transient: Cool-Down Propellant Consumption and its Effect on Total Delta-v	Mr. Jack Plank	The Ohio State University College of Engineering	USA

IAF cited paper:
iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/manuscripts/IAC-20,A5,4-D2.8,9,x59363.pdf

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iafastro.directory/iac/proceedings/IAC-20/IAC-20/A5/4-D2.8/presentations/IAC-20,A5,4-D2.8,9,x59363.show.mp4

Open paper: None found

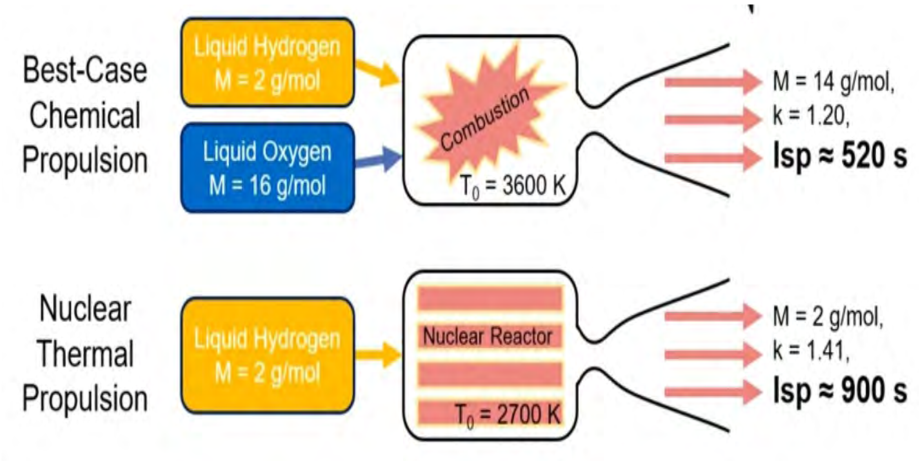
Reported by: John Davies

Mr Plank began with the specific impulse equation -

$$I_{sp} = \frac{1}{g_0}\sqrt{\frac{2kR_U T_0}{(k-1)M}}$$

He pointed out that "NTP has much higher Isp than CP without sacrificing thrust, permitting larger, faster deep space missions". In the equation To is chamber temperature, M is molecular weight, properly molecular mass, of the exhaust. For high efficiency we need high To and low M.

Best case chemical propulsion (LOX, LH2) which yields Isp = 520 seconds. The numbers here are about the same as the Space Shuttle main engine[1].



Contrasting specific impulse (Isp) for best case chemical propulsion (LOX, LH2) with Nuclear Thermal Propulsion (NTP)

Credit: Plank

Contrast NTP where the propellant is simply heated by a nuclear reactor [as in the primary coolant in a conventional nuclear power station] so the single propellant is liquid hydrogen, with molecular mass which is 7 times less. So despite the lower chamber temperature the specific impulse, shown by the equation, is much higher [note that specific impulse is directly proportional to exhaust velocity].

Plank is particularly concerned here with decay heat in NTP. The main chain reaction in the reactor produces "daughter" elements. Some of these decay to further elements after reactor shut-down [the same decay heat is what powers the radioisotope thermal generators (RTG) providing electrical power on deep space missions like Voyager and New Horizons]. This typically yields kilowatts and even megawatts of heat for hours after reactor shutdown but the falling chamber temperature results in a lower specific impulse. But the reactor will overheat without the flow through it.

The decay heat problem (credit: Plank) -

- Unstable daughter nuclei continue to decay after shutdown
- Venting LH2 during cool-down stops overheating, generates some thrust
- About 9% of the total LH2 spent during the whole maneuver
- Only 4% of the maneuver's total delta-V (58 m/s out of 1400 m/s)
- Inefficient. T_o drops during cool-down) reducing Isp.

- and in this example the cool down phase is about 10 hours. This uses propellant less efficiently.

[1] www.nasa.gov/returntoflight/system/system_SSME.html, more detail at en.wikipedia.org/wiki/RS-25

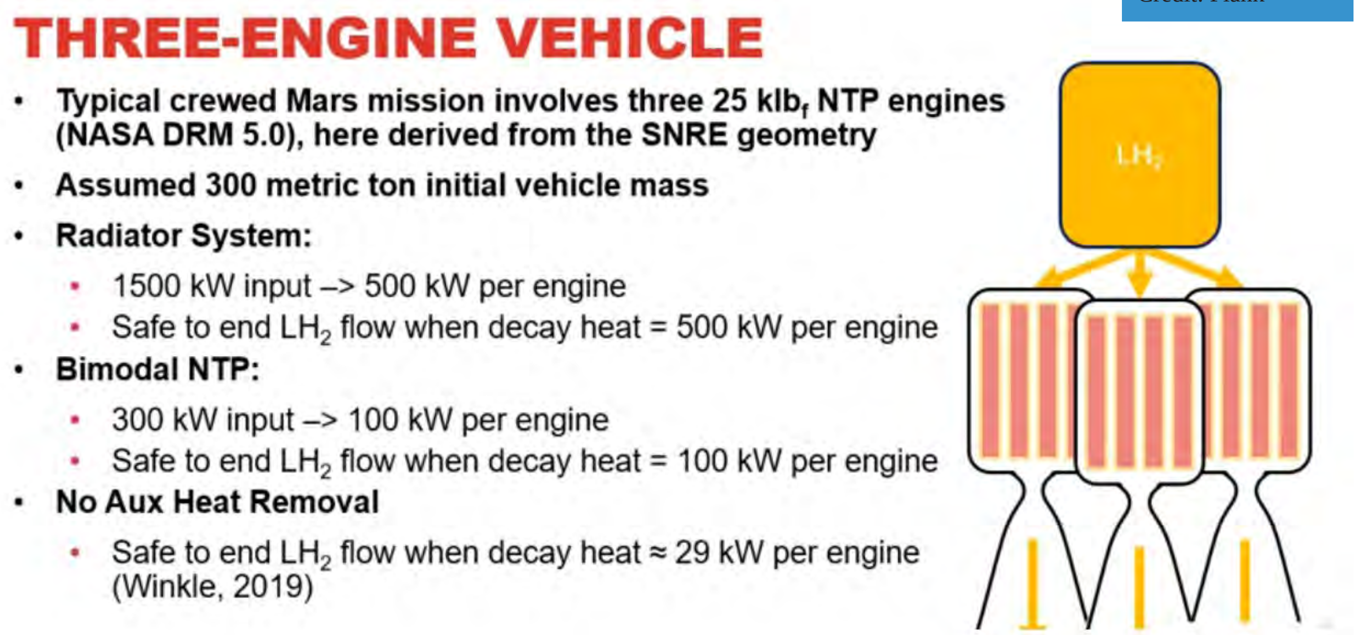
Plank lists some more efficient approaches from the literature on the subject -

- "Bimodal" Nuclear Thermal Propulsion (BNTP) - using, for example, the Brayton cycle to generate electrical power by dropping [throttling down] the reactor to a lower power level. In this case yielding 300 kW thermal and thus 40 kW electrical.
- Using radiator panels, as used by the International Space Station (ISS), to dump 1500 kW into space

But some LH2 flow to the reactor is still required.

Plank uses a reference vehicle based on the NASA Mars Design Reference Mission (en.wikipedia.org/wiki/Mars_Design_Reference_Mission).

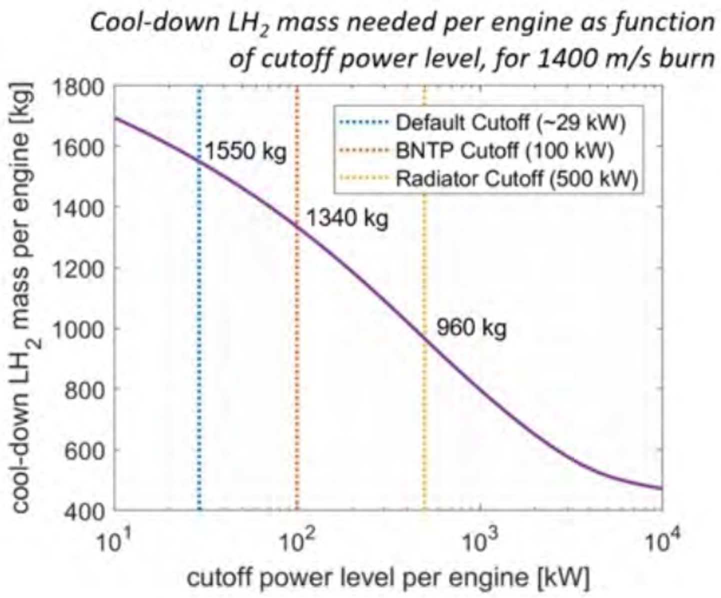
Reference vehicle
Credit: Plank



THREE-ENGINE VEHICLE

- **Typical crewed Mars mission involves three 25 klb$_f$ NTP engines (NASA DRM 5.0), here derived from the SNRE geometry**
- **Assumed 300 metric ton initial vehicle mass**
- **Radiator System:**
  - 1500 kW input –> 500 kW per engine
  - Safe to end LH_2 flow when decay heat = 500 kW per engine
- **Bimodal NTP:**
  - 300 kW input –> 100 kW per engine
  - Safe to end LH_2 flow when decay heat = 100 kW per engine
- **No Aux Heat Removal**
  - Safe to end LH_2 flow when decay heat ≈ 29 kW per engine (Winkle, 2019)

Plank's detailed calculations are in his paper. They are based on work by Emrich and Durham [2]. These result in the mass of hydrogen required per engine versus the heat being removed (cut-off power) in the three cases - no additional cooling, BNTP and radiators. He shows savings around 1000 kg of propellant mass for this reference case. And he notes that these savings apply every time the reactor is closed down. But there is a tradeoff of course - the heat removal system itself costs mass! He also analyses the benefits of heat removal in terms of propulsion. He suggests that more detailed studies are required, also adding in factors such as system complexity (bad!) and use of radiators for wider thermal control purposes (good!).



Cooldown LH2 mass required
Credit: Plank

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[2] W Emrich, Jr., "Principles of Nuclear Rocket Propulsion," Butterworth-Heinemann (2016) and F P Durham, "Nuclear Engine Definition Study Preliminary Report, Volume 11 - Supporting Studies," Los Alamos National Laboratory (1972)