The Emergence of a Fusion Propulsion Capability this Century and Implications for Exploration and Settlement Strategies

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Abstract

In recent years many companies have emerged with the goal of producing fusion based propulsion systems for space exploration. That is using the same energy generation mechanism that powers the Sun. A particular highlight has been the recent achievement of thermonuclear ignition at the National Ignition Facility which uses the method of laser driven inertial confinement fusion. This brings the possibility of applying such technology to space applications closer to fruition and concepts using this technology have been considered by NASA for missions to Mars, the outer solar system and further. Robotic missions to the outer heliosphere and beyond the Voyager probes will be possible within decades. Missions to the outer planets Jupiter and Saturn carrying a human crew may be possible in the second half of this century. Robotic flyby missions on an interstellar trajectory will be possible by the turn of the next century. These missions bring new knowledge in terms of scientific discoveries but also form the basis of an economic benefit to large scale industrialisation in space and the creation of an independent off-world economy such as based on helium-3. They also make the world ship possible. In this paper we discuss some of the concepts developed by the author consistent with these mission architectures and the broader implications for exploration roadmaps and settlement strategies of the Solar System through interplanetary flight and beyond to interstellar flight.

Keywords: Advanced Propulsion, Fusion Reactions, Strategic Roadmaps

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El surgimiento de una capacidad de propulsión de fusión en este siglo y sus implicaciones para las estrategias de exploración y asentamiento

Resumen

En los últimos años han surgido numerosas empresas con el objetivo de producir sistemas de propulsión basados en la fusión para la exploración espacial. Esto se logra utilizando el mismo mecanismo de generación de energía que alimenta al Sol. Un hito destacado ha sido el reciente logro de la ignición termonuclear en la Instalación Nacional de Ignición, que utiliza el método de fusión por confinamiento inercial impulsada por láser. Esto acerca la posibilidad de aplicar esta tecnología a aplicaciones espaciales, y la NASA ha considerado conceptos que la utilizan para misiones a Marte, el sistema solar exterior y más allá. Las misiones robóticas a la heliosfera exterior y más allá de las sondas Voyager serán posibles dentro de unas décadas. Las misiones a los planetas exteriores Júpiter y Saturno con tripulación humana podrían ser posibles en la segunda mitad de este siglo. Las misiones de sobrevuelo robótico en una trayectoria interestelar serán posibles a principios del próximo siglo. Estas misiones aportan nuevos conocimientos en términos de descubrimientos científicos, pero también sientan las bases de un beneficio económico para la industrialización a gran escala en el espacio y la creación de una economía independiente fuera del planeta, como la basada en el helio-3. Además, hacen posible la nave espacial. En este artículo discutimos algunos de los conceptos desarrollados por el autor en consonancia con estas arquitecturas de misión y las implicaciones más amplias para las hojas de ruta de exploración y las estrategias de asentamiento del Sistema Solar a través del vuelo interplanetario y más allá del vuelo interestelar.

Palabras clave: Propulsión avanzada, reacciones de fusión y hojas de ruta estratégicas

本世纪核聚变推进能力的出现及其对太空探索和定居战略的影响

摘要

近年来出现了许多生产“用于太空探索的基于聚变的推进系统”的公司。这类系统使用与太阳相同的能量产生机制。一

个特点是，近年来在国家点火装置上实现了热核点火，它使用激光驱动的惯性约束聚变法。这使得将此技术应用于太空的可能性得以提高，并且NASA已经考虑了关于使用该技术的一系列概念，以进行火星、外太阳系和更远地区的任务。机器人将有可能在几十年内到达外日光层和旅行者号探测器之外（的地区）。在本世纪下半叶，载人前往外行星木星和土星的任务可能会实现。到下个世纪初，机器人星际飞行任务将成为可能。这些任务不仅带来了科学发现方面的新知识，也为大规模太空工业化和建立基于氦-3的独立外星经济奠定了经济基础。它们也使世界飞船成为可能。本文中，我们讨论了作者根据这些任务架构提出的一些概念，以及行星际飞行对太阳系探索路线图和定居战略的更广泛影响。

关键词：先进推进，聚变反应，战略路线图

Introduction

For the human civilisation to expand beyond the Earth and the Moon, we need high energy advanced propulsion systems. These would enable spacecraft that can transport between celestial objects in a rapid transit time delivering both robotic and human crews. This suggests a need to go beyond chemical and electric based engines.

In recent years many companies have emerged with the goal of producing fusion based propulsion systems for space exploration. That is using the same energy generation mechanism that powers the Sun. This is where isotypes of hydrogen and helium can overcome the electromagnetic Coulomb barrier and combine in a reaction so that new particle products are produced. These products are ideally charged so that they can be magnetically controlled in an engine for the purpose of thrust generation.

A particular highlight has been the recent achievement of thermonuclear ignition at the National Ignition Facility of the Lawrence Livermore National Laboratory which achieved ignition and gain in 2022 (Zylstra, 2022).

This technology uses the method of laser driven inertial confinement fusion (ICF) to compress and heat up a thermonuclear fuel so it can self-ignite according to the Lawson criteria (Lawson, 1957). This is where a large array of lasers hit a fusion filled target, compress it up to high density and temperature so that it can self-ignite. The goal is to get more energy out of the pellet that went into the confinement and ignition process, a so-called net energy gain. In the very near future, it is likely that a similar but more advanced facility would be constructed that can deliver high energy gain and therefore produce energy for a national electrical supply.

Yet, there are other interesting applications of this technology once it has matured to a sufficient state of readiness. There is the possibility of applying such technology to space applications in the propulsion of a vehicle (Long, 2023). Although we are still some distance from our ability to construct such machines, we are edging closer to it and indeed spacecraft design concepts using this technology have been considered by NASA for missions to Mars, the outer solar system and further (Schulze, 1991).

It is likely that robotic missions to the outer heliosphere and beyond the Voyager probes will be possible within decades. Missions to the outer planets Jupiter and Saturn carrying a human crew may be possible in the second half of this century. Robotic flyby missions on an interstellar trajectory will be possible by the turn of the next century. These missions bring new knowledge in terms of scientific discoveries but also form the basis of an economic benefit to large scale industrialisation in space and the creation of an independent off-world economy such as based on helium-3 industrial mining.

In this paper we discuss some of the concepts developed by the author consistent with these mission architectures and the broader implications for exploration roadmaps and settlement strategies of the Solar System through interplanetary flight and beyond to interstellar flight.

We also discuss the broader implications for our technology roadmap planning in terms of securing a continued peaceful human presence in the Solar System among many different varied colonies. It will be necessary to police the 'seas' of space to ensure that the chaotic nature of nation state geopolitical relationships that have manifested on Earth do not spill over into those different colonies and thus create a divided humanity. Instead, we should be exploring the Cosmos together in peace, but this will require substantial co-operation and adherence to agreed interplanetary laws.

Securing the Solar System

Many have the goal to develop a multiplanetary species. This includes the technologist Elon Musk who has declared this an explicit goal for his company Space Exploration Technologies Corp. He has rightly realised that the bottleneck to making this happen is cheap reusable access to Earth orbit on a routine basis. When this occurs the cost of putting mass into space will not be a significant factor in human expansion.

Yet, what would it mean to have humans living and working in space? Existing together in small communities, all strongly dependent upon each other and any resources derived from local sources or via trade from Earth or even one of the other colonies. The following is speculation on specific timescales and numbers but based on an informed assessment. This is not an exact prediction based on a rigorous mathematical extrapolation of existing activities, but more of one of many in a Plethora of possible futures that might unfold. We describe this specific scenario to illustrate the sorts of problems that may require careful thought in terms of policy planning.

The locations of these future human colonies can be broadly categorised into five categories which also likely follow each other in a linear timeline. This includes (1) Earth orbital structures (2) Lunar settlements (3) Mars settlements to include Deimos and Phobos (4) Other deep space artificial structures such as at the Lagrange points (5) Other moons or asteroids further out in the solar system.

The next planned artificial habitat after the International Space Station is decommissioned is the lunar Gateway project, a large space station in the orbit of the Moon consisting of 4 – 8 people perhaps on a 1 – 3-month rotation. This should begin around the year 3030 – 2035 timeframe. In addition, it should not be a surprise if other nations and commercial companies also start constructing space stations in Earth orbit on the same timescale. By the middle of the century, we can fully expect there to be a permanent human presence in orbit of the Earth and Moon numbering several hundred people. By the end of the century this orbital population will grow to as large as 10,000 people and perhaps more.

The first lunar bases will likely be small and like an Antarctic style scientific station consisting of 6-12 people on a 3 - 6-month rotation. This should begin around the year 2035 – 2040 timeframe. By around the middle of this century they should have grown to a population that possibly numbers 100-200 people and won't just be in a single location but in several locations around the Moon. By around the year 2100 we can fully expect there to be a permanent human presence on the Moon numbering several thousand people as the first lunar cities are established.

The first crewed missions to Mars are likely to occur in the 2040 – 2045 timescale, although due to international tensions and competition in space may be as early as 2035. Since Mars missions are hazardous, some of the first attempts may result in failure, but eventually humans will settle. The first missions will see crews of perhaps 4 – 6 astronauts rotating on missions commensurate with the Earth-Mars close opposition over 18-24 months timescales. After a few iterations of this, our experience will be sufficient to have cracked survival there, such as the production of oxygen from the rocks for use as breathable air or in rocket fuel. By the middle of the century, we might expect to see a permanent presence on Mars numbering 50 – 100 people. This will be the seeds of the first city, and it will grow rapidly from this base to round 10,000 people by the year 2100.

One possible (hypothetical) scenario that we might see unfolding in the future is a divided human population split around Venus, Earth-Moon, Mars. Since the United States is the dominant space power and is the leader in pursuing lunar missions (based on the Project Apollo success) we might expect a continued dominance by the United States and its European allies (and other partners like Japan and Australasia) in Earth orbit and on the Moon. Whilst the other nations would have a presence on the Moon, they may be willing to seed management of the lunar settlement to the United States so they can focus on other domains of interest. One can imagine several stations eventually being created on the Moon and this will be the progenitor to the first lunar cities.

The Russians however, looking for an alternative base of operations, may decide to cement their love affair with the planet Venus and give priority to construction of an artificial habitat in Venusian orbit. In the past Russia successfully sent the Venera spacecraft missions to Venus between 1961 and 1984. The first of these missions was Venera 7 which successfully landed on the surface of Venus in 1970, and it provided the first direct measurements of the Venus surface.

Venera 9 landed in 1975 was another successful Russian mission to Venus and it provided valuable data on the atmosphere. Venera 13 landed in 1982, and it operated for over 4 hours, whilst also transmitting colour images and details analysis of the soil composition. Venera 14 landed in 1982 and obtained similar data.

The most recent was the Vega 1 and Vega 2 missions in 1985 which delivered a surface lander and operated for two days, whilst the Vega 2 probe continued to perform a flyby of the planet and intercept a comet. This is not to ignore the United States missions to Venus such as Mariner 2 in 1962, Mariner 5 in 1967 and Pioneer Venus 2 in 1978, but to emphasise the Russian interest in Venus.

Although we might think that constructing an artificial habitat on the planet Venus is near-impossible due to the toxic atmosphere which is made up of mainly carbon dioxide with traces of sulfuric acid clouds, which is corrosive to any materials. It has a temperature of 450°C and 90 bars atmospheric pressure, yet there is in fact a way this can be achieved. For example, it has been proposed (Landis, 2003) that large habitats can be constructed in the high-altitude stratosphere using aerostat structures as cities in the clouds. Above a height of around 50 - 60 km the surface temperature and pressure are not that different to Earth at 1 bar. These sorts of structures, in addition to orbiting stations may be a way forward for any nation that desires an independent space habitat domain of influence.

That is contingent on adequate sources of water can be provided for which there is none on Venus. Since the planet is much closer to the Sun than the Earth it also receives a lot more sunlight which allows for the possibility of considerable solar power stations. Since Venus has a thick atmosphere there would be protection from cosmic radiation (unlike on Mars). For an orbiting space station this would need sufficient thermal protection from the high temperature emission from the planet's atmosphere but also due to solar radiation and solar flares. The use of storm shelters and thick radiation shielding suggests massive structures.

The United States and its European allies may claim a special interest in the planet Mars based on the successors of their many robotic rover landings and orbital satellites. This includes the Mariner and Viking spacecraft to name some notable examples. Certainly, it is the case that these nations have achieved the most in terms of in-situ investigations of the Red Planet.

The United States success with Mars began with the Mariner missions from 1964 to 1971 by flybys and orbits of the planet. Then there was the Viking 1 and 2 missions in 1976 which landed on the surface obtaining some of the first soil and atmospheric readings planet whilst also searching for signs of life. Mars Global Surveyor entered orbit in 1996 and orbited the planet for nearly a decade. The Mars Pathfinder and Sojourner Rover touched down in 1997 and deployed the first successful rover on the surface. Mars Odyssey entered orbit in 2001 and is still operating. The Spirit and Opportunity rovers operating on the surface from 2004 to 2018. The Mars Reconnaissance Orbiter has been operating since 2005 and is still going. There are many other missions, including the Phoenix lander, the Curiosity Rover, MAVEN, InSight and the Perseverance Rover. One of the recent highlight achievements is the operation of the Ingenuity Helicopter from 2021 which became the first powered aircraft to achieve a controlled flight on another planet.

The Russians have had some success on Mars, with Mars 3 in 1971 as the first partially successful landing but with no useful transmission. The Mars 2 and 3 orbiters. The Mars 5 orbiter in 1973 which successfully entered orbit but failed within weeks. Then there was the Phobos 2 mission in 1988, but it was eventually lost as it approached the moon Phobos due to a malfunction of the on-board computer. In summary, whilst the United States and its partners have had great success on Mars, the Russians have not, and instead it could be argued that the Russian success story is better represented with their Venus missions.

Yet, there may be a competing viewpoint for which any space policy makers should take note of. In 2022 China released a report (China, 2021), in which they declared a desire to achieve Mars orbiting, landing and roving on one single attempt. They are also currently developing a 1 MWe fission reactor which would be required on such missions. Whilst China would rightly want to have participation in lunar missions, might their real intention be to secure Mars as a long-term strategic goal?

Perhaps of notable concern to the West is the progress in spaceflight being made by China. This includes with its Long March rocket family the Chang'e, Tianwen and Tiangong space stations, successful landings of spacecraft on the Moon. They have also attempted to deploy an orbiter around Mars with Yinghuo-1, but it failed due to the use of a Russian carrier. Yet they have managed to use the Zhurong Mars rover to explore the planet and "*left China's first mark there. China has achieved a leap* *from cislunar to interplanetary exploration*". They have successfully made a flyby of an asteroid Toutatis.

In a speech given from Beijing on 22nd July 2021 the former Chinese foreign minister Wang Yi stated the following in relation to the planet Mars:

> "*The planet Mars (Huǒxīng) was first detected by Chinese scholars thousands of years ago; well before the Greeks. This fact is not in dispute. Because this is not documented in the Western world is inconsequential. Huǒxīng is also Red, showing it clearly belong to our beloved Socialist System with Chinese Characteristics. Any attempt to dispute this fact is just another example of foreign hegemonic behaviour and attempts to interfere in China's internal affairs.*"

China has also made its intentions known to build a sustainable long-term human presence on Mars, according to a speech by Wang Xiaojing, the President of the China Academy of Launch Vehicle Technology (Xiaojing, 2021). He is reported to have said that China has bigger plans, beyond even a Mars sample return mission planned to launch in early 2029, and then finally constructing a Mars base. The China Aerospace Science and Technology Corporation (CASC) has apparently completed comprehensive research on mission architectures to include available launch times, the types of orbits and propulsion systems to be used. Nuclear thermal propulsion systems are likely to be involved in such missions for the Earth-Mars cargo transfer.

As far as the world is concerned, Chinese astronomers did observe Mars by no later than the 4th Century BCE and in East Asian cultures Mars is traditionally known as the 'Fire Star' based on the Wǔxíng system such as in the I Ching divination. In the West Mars was not observed through a telescope until Galileo Galilei in 1610, although it was also known to exist by the earlier Egyptian and Babylonian astronomers.

The next Year of the Dragon in the Chinese Zodiac will be in 2036, and the dragon symbolises power, strength and good fortune in Chinese culture. Prior to this is the Year of the Tiger beginning in 2034 and ending in 2035, which symbolises courage and confidence. The close conjunctions between Earth and Mars will occur in 2033, 2035 and 2037. Mars is a particularly interesting strategic goal since it is a good launching platform for missions to the asteroid belt where vast quantities of precious metals can be found. As a long-term investment strategy, it would make sense. Is it possible that China may attempt a surprise run on Mars ahead of the United States and its allies? Perhaps in the 2034 to 2037 timeframe. What would they do if they got their first? Would they claim Chinese sovereignty over the territory or at least a large part of it? How would the other nations respond? Would Mars become split over territorial lines?

It would not be an easy mission to achieve given the limited launch systems China currently has – The Long March 5. It can lift around 25 tonnes into Low Earth Orbit (LEO) or 14 tons to a Geostationary Transfer Orbit.

However, this does not have the capabilities that the SpaceX Falcon Heavy, which can carry 63.8 tons to LEO or 26.7 tons to GTO. It can also carry a payload of 16.8 tons to Mars. SpaceX has also been developing the Starship, which can carry 100-150 tons to LEO and 27 tons to GTO. It has a Block 3 variant that can carry 200 tons to LEO. In principle Starship could deliver a 100 tons payload to the surface of Mars and Elon Musk has announced both robotic and crewed missions to Mars will be attended in the very near future.

NASA has also developed the Space Launch System (SLS) which is a large rocket capable of taking a payload of up to 130 tons to LEO and up to 46 tons for a Trans-Lunar-Injection (TLI), so clearly the United States is currently in the lead for heavy lift vehicles.

However, China is developing a Super Heavy rocket the Long March 10 which will have many times the lifting capacity of the Long March 5 with 70 tons to LEO and 27 tons for TLI. One must wonder what they need it for. As well as missions to the Moon and the assembly of orbiting space stations, a crewed mission to Mars would be an obvious application. Even if one disagrees this is not their intention, it must at least be acknowledged that their capability for doing a Mars mission is increasing.

Although the scenario described above may have more in common with fiction than reality, it is one possible future that may lay ahead of us. Given this scenario, humanity may be split between Earth-Moon space under the stewardship of North America, Europe and its allies like Japan and Australia, Venus under Russia and its partners, and the planet Mars under the hotly contested stewardship of a US-China led coalition.

This scenario would imply that rather than a united humanity living in space as a multiplanetary species, we would be a divided one, where nations assert their authority over domains of space and territories, backed up with loosely held alliances. The ability of any colony to conduct trade with other colonies, based on the wealth of resources they have access to, will become a defining factor in the success or failure of those settlements.

How do any nations undertake scientific exploration missions in space and maintain peace among a divided a spatially separated group of human communities with a range of different allegiance and ideologies? They will be expected to remain consistent with the existing Outer Space Treaty (OST, 1967). A key determining factor will be the development of an advanced space propulsion capability so that vessels are able to transport robotic and human crewed payloads from one location to another efficiently.

Spacecraft Concepts for Exploration

Now that we have considered a possible future scenario that may unfold in the solar system, it should be clear that there will be a requirement for advanced propulsion technology. This will be needed to transport payloads from one place to another in a rapid transit time, but also for the purpose of colony support, protection and defence in the circumstances of political discord between different settlements or their nation state agencies for which they are allied.

Although there are many types of propulsion systems (Mallove & Matloff, 1989) that can facilitate the sorts of architectural requirements needed, we will restrict the discussion below purely to fusion based propulsion systems since this is the vehicle architectures for which the author has recently been involved in constructing.

We discuss these in the context of several vehicle architectures that span from the inner solar system to the outer solar system. This includes from Venus and Mars to Jupiter and Saturn, and then outside of the solar heliosphere into the interstellar medium. We then consider full interstellar missions to include robotic and crewed which take us to planets around other stars.

Crewed Inner Solar System

A vehicle will be needed for missions to the nearby planets, which includes Mars and its moons Phobos and Deimos and possibly for the planet Venus. In addition, due to the proximity of Mars to the asteroid belt such a vehicle would likely need to reach this distance as well. The vehicle should be capable of human carrying flights especially in support of a human colony on Mars which is likely in the very near future. It could also be used for missions to the planet Venus, and for carrying people or cargo to nearby space stations in Cis-lunar space or one of the local Lagrange points.

A concept was developed by scientists at the Lawrence Livermore National Laboratory, and it is called the Vehicle for Space Transport Applications or VISTA (Orth, 1987). It was then developed further to include a better definition of the different technologies (Orth, 2003). The vehicle would carry a 100 tons crewed payload to Mars in around 150 days, from which it would re-fuel for the journey home. The vehicle configuration has an unusual conical shaped geometry since it was desired to minimise the amount of radiation and high energy neutrons that might interact with the spacecraft structure. This was especially since the plan was to use Deuterium-Tritium fuel where a high number of neutrons are expected in the reactions.

VISTA is highly futuristic in that it claims a pellet energy gain of 1,500 which does not seem reasonable. However, it is certainly likely that an energy gain in the 100s is possible and so missions of this type will also become realisable. It is fair to say that the designers of VISTA were being overly optimistic in the claimed pellet performance which may have suggested such a vehicle would be much harder to achieve.

The spacecraft would travel with a cruise velocity of around 80 km/s with the pellets detonated at 30 Hz. It would utilise 3.72 tons of thermonuclear fuel in addition to 4,100 tons of hydrogen propellant for the purpose of thrust augmentation by boosting the mass flow rate of fuel into the reaction chamber. The pellets would be 46 mg in mass supplemented by the 50,000 mg/pellet expellant. For the pellet a laser energy of 5 MJ would have to be delivered to the target, and if operating at an efficiency of 12% this would imply a wall plug energy of around 42 MJ. The laser definition would be represented by an energy deposition and peak power of 5 MJ / 500 TW. The VISTA vehicle is illustrated in Figure 1.

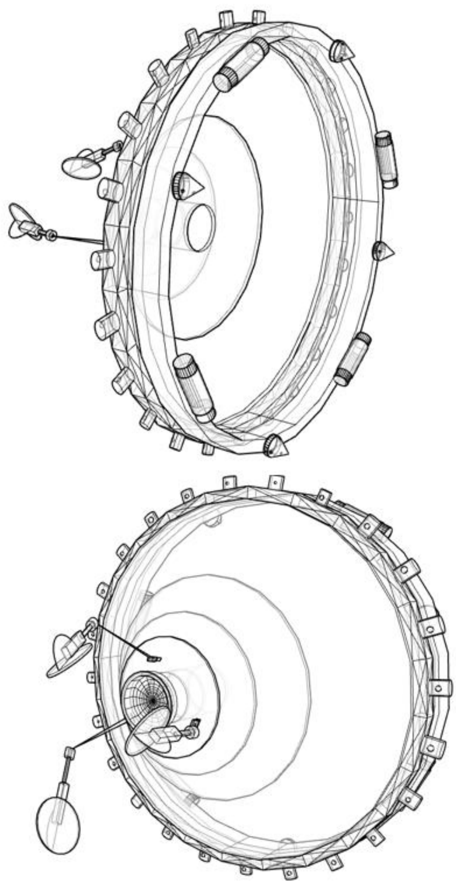

Figure 1. Crewed Interplanetary Vista Spacecraft Concept Design.

Crewed Outer Solar System

Once humans have demonstrated an ability to survive on Mars on a regular basis, we can fully expect human crewed missions to attempt even great feats of the imagination. Indeed, in the early days some of these missions will become like 'firsts' and bold pioneers will attempt to go further and faster than any missions that came before. This will provide for an environment of exciting opportunity and participation for those seeking a more meaningful purpose to existence.

Although it is much further, it is inevitable that missions to the gas giants will follow from those of Mars. These will begin as scientific survey missions, perhaps on a quick round trip mission, but they will get longer and involve more people and a broader exploration and settlement strategy than just data gathering. Perhaps of particular interest will be the many moons of the gas giants since the worlds themselves have a massive gravity field and it would be difficult for humans to enter their atmosphere. So instead, the moons would receive interest from a settlement and mining point of view. This includes for Jupiter where there are 95 moons, then 146 moons for Saturn, 16 moons for Neptune and 28 moons for Uranus. Missions even further such as to Pluto with its 5 moons may also become of interest.

An example of the sort of vehicle that this might involve during the early exploration phase is the Discovery-III (Long, 2024) and is illustrated in Figure 2. It is a redesign of a NASA Discovery-II design (Williams, 2005) but involving an ICF engine. They both have their legacy in the Discovery-I of the movie '2001: A Space Odyssey' and the novel of the same name (Clarke, 1968). The main mission is to carry a crew of 6 – 12 astronauts in a total payload mass of 172 tons to Jupiter in 118 days and Saturn in 212 days. The crew would be contained within a rotating habitat section for the purpose of generating an artificial gravity environment.

The spacecraft would travel at a cruise speed of ~70-80 km/s detonating 2.88 mg deuterium-helium-3 thermonuclear fusion pellets at a rate of 100 Hz, augmented with 450 mg/pellet of expellant injected into the reaction chamber to produce a thrust of around 21 kN. The total fusion fuel requirement would be 4.74 tons (Jupiter) and 5.29 tons (Saturn), supported by 740 – 830 tons expellant propellant. For the pellet a laser energy of 26 MJ would have to be delivered to the target, and if operating at an efficiency of 7.7% this would imply a wall plug energy of around 336 MJ. Therefore, the laser definition would be represented by 26 MJ / 2153 PW.

Crewed Interplanetary Peacekeeper

With various nation states from Earth engaged in settlement of the Solar System and the wide number of separate colonies that will result, there will be a need to maintain the peace and to give assistance to any settlements in need. This will require military-style vessels, like what the U.S Navy employs in service today to maintain the laws of the Sea. We refer to these as Peacekeeper vessels and an example is shown in Figure 3 for the U.S.S Heinlein. It will be especially important to ensure the trade routes between settlements are not interrupted.

The spacecraft would have a payload mass of 300 tons which includes a crew of 12 – 24 astronauts in addition to several types of sub-probes. These include large and small landers but also two shuttle vehicles which can dock with orbiting space stations, assist with extra vehicular activity or land on small moons. The vessel would patrol a

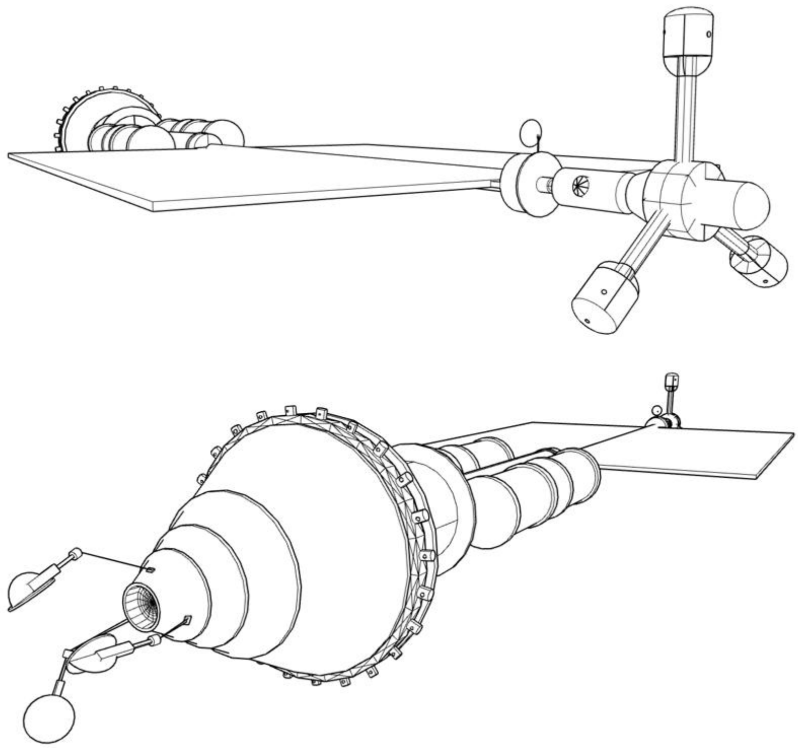

Figure 2. Crewed Interplanetary Discovery-III Spacecraft Concept Design.

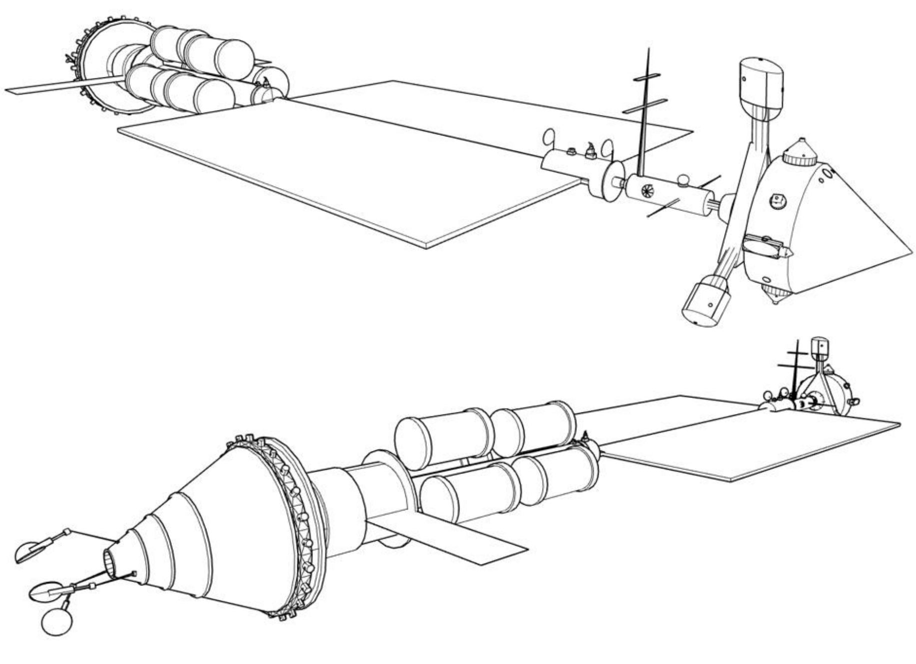

Figure 3. Crewed Interplanetary U.S.S Heinlein Spacecraft Concept Design.

set of orbital trajectory routes but have additional propellant so that it can go-off orbit to perform other missions. It would be highly equipped with instrumentation sensors such as radar. Since it is a military vessel, it would also carry a minimum armament and the use of non-lethal laser photon canons which can disable the electronics of another vessel in the event of conflict but would not harm the crew.

The spacecraft would travel at an average velocity of around 100 km/s. This means that, depending on the position of their orbits, the vehicle could reach Mars in 25 – 30 days, Jupiter in 90 – 100 days and Saturn in 160 – 180 days. We might imagine several of these vehicles operating simultaneously along the orbital trajectories. The laser and pellet specification would be like the Discovery-II but with a slightly enhanced fuel loading and increased pulse frequency to 150 Hz to facilitate the higher acceleration rate, so that a thrust of around 30 KN is produced from the engine. The enhanced performance means they can manoeuvre for different situations and intercept other vessels when required.

Robotic Exo-Heliospheric

The SunVoyager is a spacecraft concept designed to go outside the solar system and deep into interstellar space (Long, 2023,2024) and it is illustrated in Figure 4. It is a post-Voyager mission to explore the Kuiper belt and interstellar medium. The solar heliosphere is the boundary of our sun's plasma extent and where the shock wave generated meets the galactic winds of other stars. SunVoyager would also explore some of the trans-Neptunian objects such as dwarf planets, some of which are perhaps yet to be discovered.

Its primary mission however would be to use the gravitational lens focal point to image exoplanets around other stars (Turyshev, 2018). This is a consequence of the General Theory of Relativity where distant objects can be magnified by a factor of ~104 (Maccone, 2009). It would also perform high precision measurements of the position and motion of other stars as a contribution to astrometry.

The SunVoyager would travel at a velocity of around 720 km/s and reach 500 – 1000 AU in a timeframe of around 6-10 years. It would carry a 10 – 100 tons payload depending on the type of mission. A science instrument like the Hubble Space Telescope would be around 10 tons in mass. Since it does not have artificial gravity spin it is not designed to carry humans but only a robotic payload. It could carry a range of payloads and travel at a fast transit speed, it could also be used for other missions in the solar system, although its primary role would be deep space exploration.

It would use 5.76 mg pellets of deuterium-helium-3 augmented with 10 mg/pellet expellant, detonated at a pulse frequency of 10 Hz. The total thermonuclear fuel would be 10 tons and the total expellant would be 17.36 tons. It would require a laser energy deposition of around 43.5 MJ and we assume a laser efficiency of 24.3% which suggests an initial wall plug energy of 179 MJ. Therefore, the laser definition would be represented by 43.5 MJ / 2900 PW. In the calculations optical flash pump lasers were assumed such as for NIF but such a vehicle would likely need to adopt Diode Pumped Solid State Lasers (DPSSL) as was proposed for the VISTA design, since in principle these can operate at a much higher efficiency and don't have the same laser-plasma instabilities associated with NIF type designs.

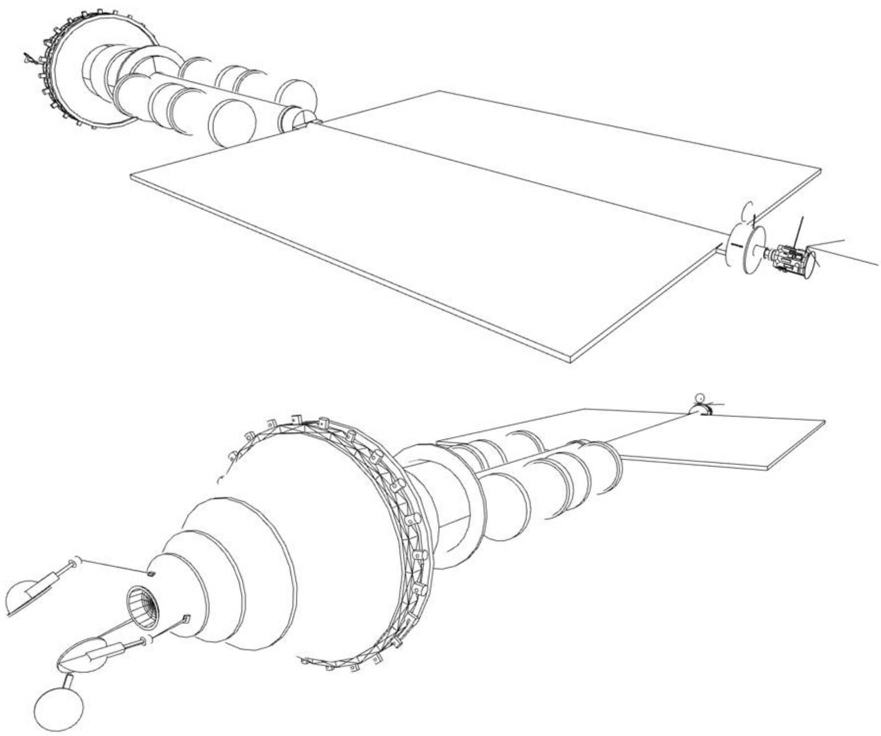

Figure 4. Robotic Interstellar Precursor SunVoyager Spacecraft Concept Design.

Interstellar Explorers

Once the interplanetary and exo-heliospheric missions had been demonstrated, the next priority would be the development of robotic probes that can traverse interstellar distances. This is a subject that is becoming more topical since we have discovered thousands of exoplanets around other stars (Budrikis, 2022) and the astrophysical and astrobiological case for interstellar missions is strong (Crawford, 2009).

One of these is the Resolution concept design which is a flyby probe (Long, 2023). The Resolution would reach a cruise velocity of 13,560 km/s and reach the nearest stars at 4.3 light years distance in a trip time of around one century. Using Deuterium-Helium-3 fuel it would require around 2,000 tons to complete the mission. However, as a flyby probe it would have a limited encounter time in the system and not be able to deploy scientific sub-probes to explore any exoplanets. Yet the initial data that it collected would be essential to any future missions.

Following this would be the full-up rendezvous mission and this vehicle concept design is called Pegasus which is illustrated in Figure 5. It would require a massive 43,300 tons of Deuterium-Helium-3 fuel and millions of pellets would be detonated at a rate of 1,000 Hz. The Pegasus is parallel thrust system with four large engine nozzles, and this is designed to boost the thrust profile and reduce the acceleration and deceleration time of the mission. It would carry a payload of around 150 tons which would consist of numerous orbiters, atmospheric penetrators and surface landers so that any celestial objects in orbit around the destination star, could be investigated properly. It would travel at a cruise sped of 13,680 km/s or 0.045c, reach its destination after 100 years of flight time and continue to operate for several decades after.

The current design configuration for Pegasus involves the use of a 72 mg fuel pellet using a laser energy of 145 MJ delivered to the target. Assuming an optimistic laser efficiency of 25% in the future this would require a wall plug energy of 580 MJ. Therefore, the laser definition would be represented by 145 MJ / 903 PW. Clearly substantial progress in technology breakthroughs would be required before such a mission becomes feasible.

Crewed Interstellar

Once humanity had fully explored the local star systems with its flyby and rendezvous robotic probes, it would then become feasible to send very large, crewed habitat structures as a part of a large expansion and settlement strategy. These are very large world ships, the size of small moons, perhaps 10^{11} – 10^{12} kg in total mass. Such concepts have been explored by others using external nuclear pulse engines (Bond & Martin, 1984) but also more recently using ICF engines by this author (Long, 2023/2024). Such a vessel would have a carrying capacity of 1 million people and the population would grow to as large as 10 million people over the 850 years or so trip time travelling at a cruise speed of 1,550 km/s or 0.52c.

Since the vessel is so large it would require something like 1,024 engines operating in parallel, with each pellet detonated at a rate of 100 Hz. Each pellet would be 230 grams in mass augmented with 4.85 kg/pellet expellant injected into the exhaust stream. Each pellet detonation would require 170 TJ on the target and assuming a 25% laser efficiency the total wall plug laser energy required would be 680 TJ.

The vessel would be capable of visiting star systems, creating a colony, and then moving onto another star system. These would be the equivalent of artificial worlds in their own right, 115 km long cylinders spinning for artificial gravity. They are like the O'Neil habitat concepts developed in the 1970s (O'Neil, 1976) but with the difference they are propelled by large sets of engines and do not stay in one position. Although world ships sound like a fantastic idea, in a future age of autono-

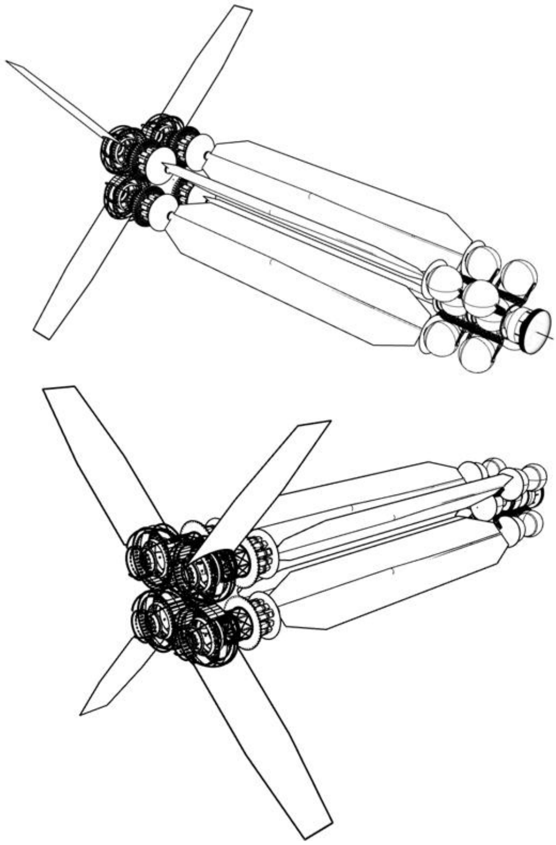

Figure 5. Robotic Interstellar Pegasus Rendezvous Spacecraft Concept Design.

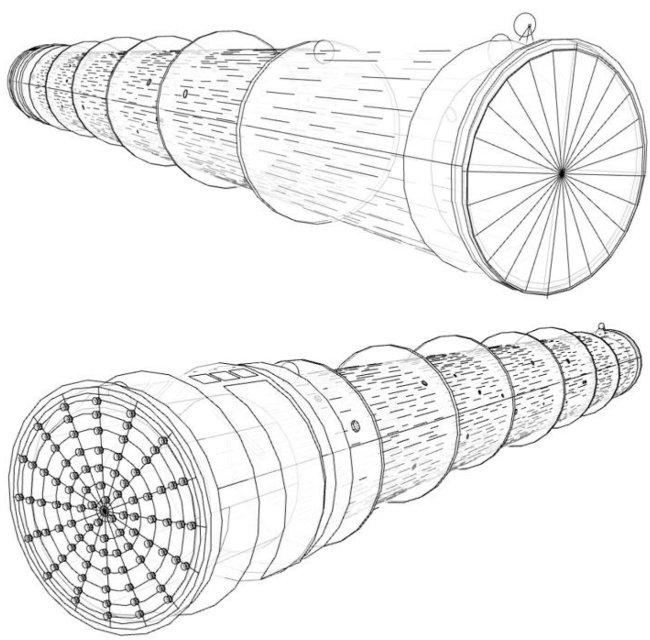

Figure 6. Crewed Interstellar Worldship Spacecraft Concept Design.

mous self-replicating robots driven by artificial intelligence and where the resources of the Solar System are at our disposal, they are become feasible and economically viable.

Cost of an Interstellar Program

The costs of any mission are split into a research and development phase, construction and production phase, and a mission utilisation phase. There is also the cost of the helium-3 mining. Taking together we refer to this as the Capital expenditure for the project or CAPEX.

In terms of getting to the point of constructing and launch our first interstellar rendezvous probe, calculations by this author show that this will likely be of order \$70 Billion (Long, 2024). Approximately half of this is attributed to the cost of helium-3 mining acquisition at a cost of \$1.4/gram (compared to the current cost of \$1400/gram). This would be captured from the atmospheres of the gas giants and would need a substantial space architecture in place to facilitate the industrial base. They are also based on launch costs coming down from the current \$100 million per launch down to \$10 million per launch.

The above cost is just for the interstellar rendezvous probe development. To get to that point requires a lot of technology development which is then managed through milestones and stage gates best measured by the development of vehicle architectures at a lower velocity and energy requirement. Taking this entire program into account, we assess that the total program cost will be of order \$310 Billion. This cost analysis did not include the Peacekeeper mission concepts however which would be an additional cost and funded largely through a military budget.

This is the expenditure leading up to the first interstellar rendezvous mission around 2150 and through the mission utilisation phase of that mission which would complete around 2250. This means a program that is over a 240-year timespan and so amounts to around \$1.3 Billion per year or \$13 Billion per decade. This is approximately 1/20th the current NASA budget which in 2023 was around \$25.4 Billion or 0.4% of US Federal spending of \$6.2 trillion. Therefore, the interstellar program is costed at 6.5 - 12.2 times the NASA budget. On the assumption that the NASA budget stayed approximately constant (relative to inflation) and half of its budget was directed towards an interstellar program along the lines described above (i.e. \$12.7 Billion) then the total program could be paid for within \$13 - 24.4 years.

Critical to the development of this program will be the individual technologies required to undertake the different missions. For a fusion propulsion system this includes hydrogen and helium storage systems, to include at cryogenic temperatures. This includes pellet injection systems for high frequency of detonation. This includes large magnetic nozzle systems with superconducting field coils. This includes magnetic pick-up coils and transmission lines for induction bootstrap power systems.

Since the missions involve autonomous payloads, this may require a high degree of computing power to include artificial intelligence systems so that decisions can be made in-situ and without delay. This becomes more important the further from Sol the missions get into interstellar space.

The individual technologies would be mapped to technology readiness levels (Mankins, 1995) and then to actual missions so that stage gates could be defined along any strategic and technological roadmap. Such a program will likely require a high degree of central management control, such as through a national space agency or commercial operator, and then linked to other agencies and other operators across international boundaries. This would be an enterprise from which all of humanity contributes and all nations reap the economic benefits as space is opened to new enterprise.

As nations seek to explore and settle the celestial bodies of our solar system, they will be required to remain consistent with international laws and treaties, including the Outer Space Treaty which explicitly states that outer space, including Mars and other celestial bodies is not subject to national appropriation by any means. This means that no individual nation can claim sovereignty or ownership over another world.

However, with increasing geopolitical tensions on Earth, if those relationships are to continue into space, then it there is no guarantees that nations will remain compliant with these treaties which may be seen as outdated or inconsistent with nation state ambitions. To ensure that nations do behave consistent with treaty obligations this may require a military style policing of the Solar System to ensure freedom of navigation and protection of interests.

Overall, the exploration of space, the Solar System and beyond will be a lot cheaper if nations co-operate together for mutual benefit. Although nation-state competition may lead to an acceleration in technologies, it would be far more costly. Ultimately, this is the test of an emerging civilization and whether it is fit to expand into the wider cosmos, based on its intentions of peaceful exploration or otherwise.

Conclusion

In this paper we have described the expansion of humanity out into the Solar System using a set of spacecraft vehicle designs based on inertial confinement fusion engines. Whilst we are not wedded to this specific method of propulsion, we use it here as an example case study for one possible future.

The exploration of the Solar System presents an exciting opportunity for humankind to learn about itself and how it can adapt to different planetary environments. As well as on planets, this may also include settlement posts on Moons, asteroids and within orbiting artificial structures. The first settlement activities are likely to occur around Cis-Lunar space but also around the planets Venus and Mars and the surrounding asteroid belts. Settlements further afield, such as on the moons of some of the gas giants may then follow as a part of industrial space activities.

The one factor that places uncertainty on the future is the current chaotic state of human civilisation. Our constant geopolitical divisions and nation state conflicts risks spilling over into the wider domain of space. This would not create the conditions for humanity exploring space at peace with each other, but instead will create divided colonies each with their own agendas and competition for resources. We have argued that to mitigate this it may be necessary to design a group of Peacekeeper spacecraft vehicles that have the function of policing the Solar System, protecting human colonies and resources, and maintaining the peace between those different habitats. After all, in the history of planet Earth the stability of the world has been provided by the security of the Seas and there is no reason to think this same philosophy wouldn't apply in space.

Limitations and Bias

Predicting the future is always a challenge. One can extrapolate from knowns but then there are the unknowns. This is a major caveat to any conclusions concerning potential trends in technology and geopolitical relationships in space.

Conflicts of Interest

There are no conflicts of interest associated with this work.

Ethical Obligations

There are no ethical obligations associated with this work.

References

Bond, A., Martin, A. R. (1984). World ships – an assessment of the engineering feasibility, *Journal of the British Interplanetary Society*, *37*(6), 254-266.

Budrikis, Z. (2022). 30 years of exoplanet detections, *Nature Reviews Physics*, *4*, 290.

Clarke, A. C. (1968). 2001: A Space Odyssey, Hutchinson.

Crawford, I. A. (2009). The astronomical, astrobiological and planetary science case for interstellar spaceflight, *Journal of the British Interplanetary Society*, *62*(11/12), 415-421.

Landis, G. A. (2003). Colonization of Venus, conference on human space exploration, space technology & applications international forum, Albuquerque, NM, 2-4 February 2003, *AIP Conference Proceedings*, *654*, 1193-1198.

Lawson, J. D. (1957). Some criteria for a power producing thermonuclear reactor, technical report for the Atomic Energy Research Establishment, Harwell, England, UK, AERE GP/R 1807, December 1955, *Published Proceedings of the Physical Society*, B, *70*(1).

Long, K F. (2022). Interstellar propulsion using laser driven inertial confinement fusion physics, *Elsivier Universe*, *8*(8), 421.

Long, K. F. (2023). Sunvoyager: interstellar precursor probe mission concept driven by inertial confinement fusion propulsion, *Journal of Spacecraft & Rockets*, *60*(3).

Long, K. F. (2023). Application of the HeliosX ICF advanced propulsion mission analysis code to perturbed interstellar design models, *Journal of the British Interplanetary Society*, *76*(3), 94-111.

Long, K. F. (2023). Population demographics & other issues for the massive Ra World Ship model - part 1, *Journal of the British Interplanetary Society, 76*(11), 262-272.

Long, K. F. (2024). Discovery III: missions to the outer planets using inertial confinement fusion propulsion, accepted in *Journal of Spacecraft & Rockets.*

Long, K. F. (2024). Development of the SunVoyager interstellar precursor probe driven by inertial confinement fusion propulsion, *Journal of Spacecraft & Rockets*, Published online. https://doi.org/10.2514/1.A36045

Long, K. F. (2024). Inertial confinement fusion propulsion for the massive Ra World Ship model - part 2, *Journal of the British Interplanetary Society, 77(4), 119 – 137.*

Maccone, C. (2009). Deep space flight communications, exploiting the Sun as a gravitational lens, *Springer*, Berlin.

Mallove, E., Matloff, G. (1989). The starflight handbook, a pioneers guide to interstellar travel, John Wiley & Sons Inc.

Mankins, J. C. (1995). Technology readiness levels, a white paper, NASA.

O'Neil, G K. (1976). The high frontier: human colonies in space, Space Studies Institute, Space Frontier Foundation.

Orth, C. D., Klein, G., Sercel, J., Hoffman, N., Murray, M.,Chang-Diaz, F. (1987). The Vista spacecraft - advantages of ICF for interplanetary fusion propulsion applications, UCRL-96676, presented IEEE 12th Symposium on Fusion Engineering, Monterey, California, 12-16 October 1987.

Orth, C. D. (2003). Vista: a vehicle for interplanetary space transport applications powered by inertial confinement fusion, LLNL, UCRL-TR-110500.

Schulze, N. R. (1991). Fusion energy for space missions in the 21st century, NASA TM-4298.

Turyshev, S. G., Shao, M., Alkalai, L., Friedman, N., Arora, S. Weinstein-Weiss, Toth, V. T. (2018). Direct multipixel imaging of an exo-earth with a solar gravitational lens telescope, *Journal of the British Interplanetary Society*, *71*(10), 361-368.

Williams, C. H., Dudzinski, L. A., Borowski, S. K., Juhasz, A. J. (2005). Realizing 2001: a space odyssey: piloted spherical torus nuclear fusion propulsion, NASA/TM-2005-213559, AIAA-2001-3805.

Xiaojing, W. (2021). Speech to the global space exploration (GLEX) conference, 16 June 2021, St Petersburg, Russia.

Zylstra, A. B., Kritcher, A. L., Hurricane, O. A. (2022). Experimental achievement and signatures of ignition at the National Ignition Facility, *Physical Review E*, *106*, 025202.

China's Space Program: A 2021 perspective. (2022). The State Council Information Office of the People's Republic of China.

Treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies. (1967). United Nations Office for Outer Space Affairs.