

Propulsion for Interstellar Space Exploration

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Abstract – The requirements of precursor interstellar missions are beyond the performance of chemical propulsion, even if accompanied by gravitational assist. A good compromise between performance and technological availability is found in solar sails, which allow to perform such missions at a limited cost and with limited technological studies. For a more distant future beamed energy sails and nuclear propulsion are both worth developing: the first one for fast and smaller probes, while the second one is an enabling technology for a very wide range of future space missions.

1 INTRODUCTION

Time is ripe for the first missions in the interstellar space. The scientific goals include the study of the Heliopause and of the interstellar medium, astrometry with a very long baseline, the study of the gravitational lensing effect of the Sun and the encounter with some Kuiper belt object. Such missions involve technological achievements such as the testing of advanced propulsion systems for long periods of time, the development of highly automated probes and of very long range communication systems. They would actually be *precursor interstellar missions* as they will pave the way towards true interstellar missions.

The scientific community is divided on the issue of interstellar missions and many scientists believe that they will belong forever to the realm of dreams, perhaps with the exception of a few sporadic robotic flybys of the nearby stars. However, many think that eventually true interstellar travel will prove to be feasible and that interstellar expansion is an unavoidable outcome of human evolution. The hypothetical *Conscious-Life Expansion Principle* (CLEP) in its Strong Form states [1] *An intelligent and self-aware species evolving on a planet is able to set about space exploration eventually. This enterprise is neither an option nor a casual event in the species' history, but it represents an obligatory way for the diffusion of high-level life outside the normal place where it developed.*

The Interstellar Space Exploration Committee (ISEC) of the International Academy of Astronautics deals with very deep space exploration. Quoting from the Terms of Reference of the ISEC [2], *the purpose of the Interstellar Space Exploration Committee (ISEC) is to study and assess the problems and issues involved in the manned and unmanned exploration of interstellar space. The subject will be pursued not only in its scientific, technical and economic aspects, but also in terms of its philosophical and anthropological implications.* However, as these issues concern a far future, the ISEC promoted a number of symposia (held in 1996, 1998 and 2000)

devoted to the study of *realistic, near-term, advanced scientific missions* directed toward the *outer solar system and beyond*, and it enlarged its area of interest to the part of the solar system extending beyond the orbit of Jupiter.

It has been suggested [3] that the term *realistic* should mean: 1) using present-day Physics; 2) requiring current or near-term technology; 3) requiring as low cost as possible (compatibly with feasibility); 4) entailing data return times well less than a normal job lifetime; 5) involving truly international co-operation.

Requirement 4), particularly if coupled with requirement 2), sets very strict limits to the goals of the missions, which cannot exceed the simplest precursor missions.

2 PROPULSION REQUIREMENTS FOR VERY DEEP SPACE MISSIONS

Chemical propulsion, characterized by low specific impulse¹ (Table 1) but enabling to build engines with very large thrusts (figure 1), falls short for deep space missions. Although the near interstellar space can be reached using chemical propulsion, aided by gravitational assist, no mission in interstellar space can be performed in a reasonable time without improvements in propulsion. Apparently, missions outside the solar system are not so demanding from the viewpoint of propulsion: to exit the solar system from the surface of the Earth a ΔV of just 16.5 km/s is sufficient. However, a far higher ΔV is required to avoid very long mission times: to obtain a hyperbolic excess velocity of 20 A.U./year (95 km/s) with a single burst at the surface of the Earth, a ΔV of about 97 km/s is required, a performance completely beyond chemical propulsion. The mentioned figures must be considered just as a rough order of magnitude, as both a lower (not much) or higher value can be obtained depending on how the actual mission is designed.

To assess some orders of magnitudes, the minimum requirements for various missions in terms of ΔV and specific impulse are reported in Table 1 [4] together with the specific impulse of some of the propulsion concepts presently used or under study. The relationship between specific impulse and thrust is shown in figure 1 [5]. Note that both the table and the figure are indicative and give only orders of magnitudes; some points are controversial, like the line labelled 'gas core nuclear'.

Four spacecraft (the *Voyager* and *Pioneer* probes) are now travelling into interstellar space, with speeds between 2.2 and 3.5 A.U./year (10.5 and 16.6 km/s). This performance was made possible by clever use of gravity assist: no missions beyond Mars orbit was performed without it and the lack of availability of a powerful enough rocket compelled to exploit the gravity assist of Venus (twice) and of the Earth even for the Jupiter mission *Galileo*. The clever use of gravity assist is unquestionably a success, but it doesn't come without drawbacks, particularly when used to reach the outer planets via Venus: the large increase of the mission duration and the need of travelling in the radiation-rich regions of the inner solar system affect the reliability of the probe and raises the costs linked with a very long mission, as testified by the problems encountered by *Galileo*.

A Sun flyby, perhaps preceded by a flyby of Venus, accompanied by a perihelion burn, and then followed by a flyby of Jupiter can send a probe out of the Solar system with a hyperbolic

¹The specific impulse is here defined with reference to the unit mass of propellant. It thus coincides with the ejection velocity and is measured in m/s.

Table 1: Characteristics of various propulsion systems (EB: Electron Bombardment; HEDM: High Energy Density Matter; LFA: Lorentz Force Accelerator; MPD: Magneto-Plasma Dynamic) and order of magnitude of the minimum requirements for different types of missions.

Propulsion	I_{sp} (m/s)	Status	Mission	ΔV (km/s)	I_{sp} (m/s)
Chemical - Solid	2,800	used	Planetary	10	10,000
Chemical - LOx - LH2	4,500	used	100-1000 AU	100	100,000
HEDM	10,000 - 20,000	study/dev.	10,000 AU	1,000	1×10^6
EB Ion thrusters	25,000 - 100,000	used	Interstellar	30,000 (0.1c)	30×10^6
MPD - LFA	110,000	study/dev.			
Nuclear- thermal	9,000 - 10,000	study/dev.			
Nuclear-electric	50,000	study/dev.			
Gas Core Nuclear	45,000	study/dev.			
Pulsed Nuclear	100,000	study			
Fusion	up to 1 million	study/lab. res.			
Antimatter	up to 20 millions	study/lab. res.			
Solar Sails	--	study/dev.			

excess velocity up to about 10 A.U./year even with the use of chemical propulsion. This final velocity is still low and the perihelion of the trajectory must be quite close to the Sun, with all the ensuing problems related to heating and radiation and long mission time.

Several alternatives to chemical propulsion will be available in a short time. Although solar electric propulsion has already been used with success in the *Deep Space 1* mission, it is not adequate for a precursor interstellar mission, where low thrust must be applied for a long time, with the probe getting at very large distances from the Sun, where solar panels lose their efficiency. On the contrary solar sails, nuclear electric propulsion and nuclear (fission) thermal propulsion are all viable alternatives requiring no actual breakthrough in propulsion technology.

Other concepts requiring greater technological developments are those based on laser or microwave beamed energy systems, while nuclear thermal rockets, based on fusion, and anti-matter devices require even greater effort. finally, it is possible that other propulsion concepts based on substantial advancements in physics will be available in the future, likely too late for interstellar precursor missions. They are actually not needed for missions of this class, while being enabling technologies for true interstellar missions.

3 SOLAR SAILS

Although the thrust supplied by solar sails decreases fast with increasing distance from the Sun, they are adequate for missions outside the solar system if a close Sun flyby is performed. The closer the sail gets to the Sun the higher is the velocity with which it exits the solar system. There are however limitations to how close to the Sun a sailcraft can reach, owing to thermal and radiation problems. If the sailcraft is light enough, it is possible to perform the “angular momentum reversal” [6] manoeuvre, in which the spacecraft sails outside the orbit of the Earth while reducing its heliocentric velocity, until it moves in a direction opposite to that of the starting planet. The spacecraft falls toward the Sun and, by suitably manoeuvring the sail, the exit velocity from the solar system can be in the range of 10-20 A.U./year.

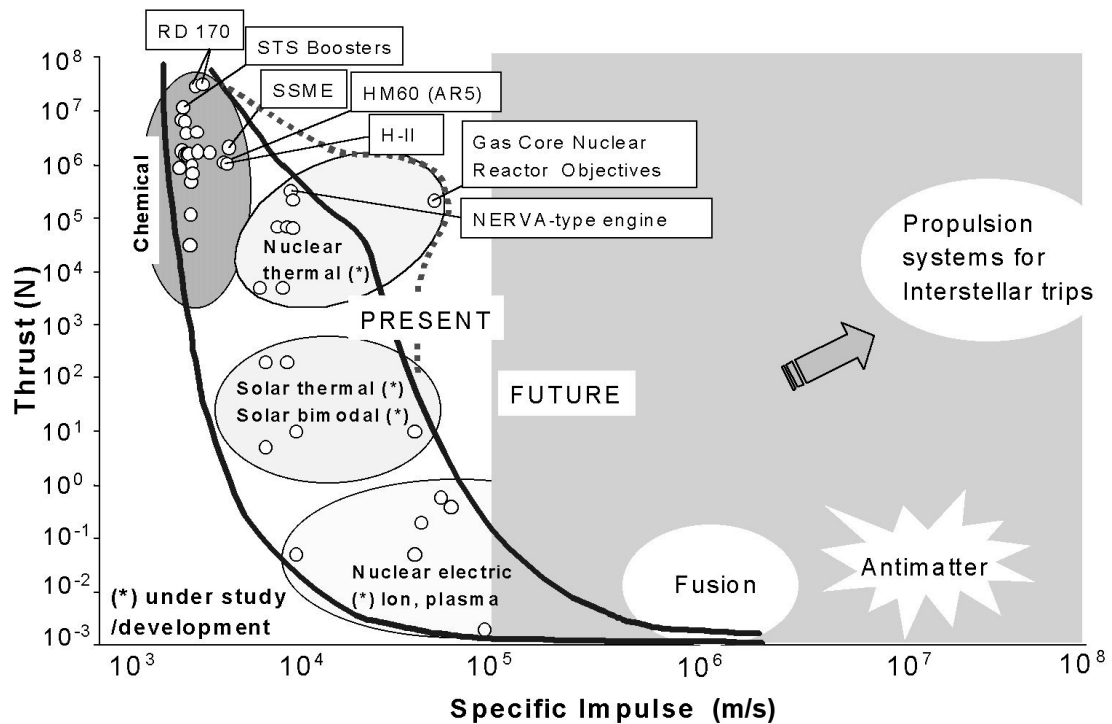


Figure 1: Performances of various propulsion concepts.

To achieve these performances the sail must be particularly light and very thin, all-metallic sails must be used. The deployment in space of such sails is by no means easy and has never yet been attempted; an alternative is the deployment of a sail with a plastic backing which can be removed either by photolysis or by other means [7]. A number of papers has been published on the subject by the work group which studied the Aurora mission.

An extended bibliography on the various types of sails (canopy, rigid, inflatable and rotating sails) can be found in [8]. Canopy sails, in the form of parachute or pillow sails, are very simple and easily deployed and hence seem to be the most convenient alternative; however they are not stable and must be kept unfurled by some structural device. A parachute sail in space tends to collapse toward a closed position as the only force which keeps it unfurled is the radial component of the light pressure, which vanishes if the sail is flat and reaches sufficient values only if the sail is much curved. As a result, a parachute sail must be very slack, with the twofold drawback of giving way to internal reflections of the light and to increase the actual area of the sail with respect to the effective area seen by the light: in the case of a spherical shape, the actual area is twice the effective one, doubling of the mass of the reflecting surface. Even worse is the situation for the pillow sail, for which a stable configuration does not exist. To keep a parachute or a pillow sail unfurled it is possible to use a small inflatable torus at its periphery or, as an alternative, to rotate them in such a way centrifugal acceleration keeps the surface reasonably flat.

Rigid sails have been extensively studied and described [9]. They can have the shape of a square ('clipper' or square sail), of a number of panels (butterfly sails, tri-sails, quad-sails, etc.) or of a circle (round and annular sails). In all cases at least a few members of the structure are

subjected to compressive loads and buckling. Even if several independent evaluations lead to a figure as low as 50 g/m for the structural beams, they add considerable mass to a large sailcraft. The need of a complex structure (lattice beams, masts, stay wires) results in deployment problems. Although many solutions have been proposed, they all require extensive experimentation in space: small sails can be built using deployable beams already built for other purposes, but they are just demonstration devices. Even more complex is the structure proposed for 'lattice sails' [9], which at any rate require also rotation for reaching the required stability.

Also inflatable sails are widely described in the literature [8]. Hollow body sails are similar to balloons of different shapes, with a reflecting surface acting as a sail. With proper dimensioning, the reflecting surface can be kept reasonably flat. They can be very easily inflated in orbit without the need of complex operations, but they are heavy due to the mass of the inflation gas (large, in spite of the very low pressure inside the sail, owing to the enormous volume) and to the actual surface of the balloon, larger than twice the effective surface of the sail. The mass per unit area of the back part cannot be lower than that of a conventional sail, leading to more than doubling the mass of the sail with respect to that of the reflecting surface. A large inflated balloon offers a very large area to incoming micrometeoroids and it is likely that a puncture occurs in a short time, causing a catastrophic failure. A rigidizable membrane may be used: the balloon is converted into a rigid shell after inflation so that the gas is needed to deploy the sail but not to keep it unfurled, and can be eliminated after the sail is deployed. However, once the inflation pressure is no more present, the stresses in the membrane become compressive at least in some zones, giving way to elastic stability problems as for all rigid solar sails and the wall thickness designed to withstand buckling is too large to be feasible. This consideration doesn't apply to inflatable and rigidizable antennas, whose much smaller size allows to withstand compressive loads.

Rotation has several times been suggested to counteract compressive stressing in solar sail structures. It can be applied to almost all the above mentioned structures and other peculiar ones, one of the most interesting configurations of a rotating sail craft being the heliogyro [9]. However, rotation is not free of drawbacks: a rotating sail craft will experience huge gyroscopic moments, which are particularly strong in large, slow spinning, objects, as solar sails: the ability to manoeuvre of a large rotating sail is questionable, and the stressing due to manoeuvring may be large. There are also rotordynamic instabilities which are still to be studied in detail, and it is very likely that vibration modes whose frequency is lower than the rotation frequency are unstable [10]. These unstable modes could be stabilized only through active vibration control, which adds to the complexity of the system. Rotating sailcrafts can be easy to deploy, provided that the rotation rate and the deployment rate are constantly kept under close control.

A simple sail geometry, allowing to reach a very high ratio of the mass of the sail over the overall structural mass has been described in [11]: a lightweight inflatable torus to which the cables connected to the payload are attached, can be used to both deploy and then to keep unfurled the sail. The very small cross section of the inflated torus exposed to micrometeoroids and the possibility of building it with redundance, owing to the small overall mass, allows to use it with confidence even for long missions. If the trajectory reaches the inner solar system, the payload and the other parts of the spacecraft need to be set in the shadow of the sail and a pillow shape may be preferred to a parachute shape [12].

The only solar sail which has been tested in space, the Russian sail *Znamia 2* deployed from an automatic cargo *Progress*, was a 20 m diameter rotating round sail.

4 BEAMED ENERGY DEVICES

An alternative to solar sails which may be implemented within a short term is beamed (laser or microwave) sails. By beaming a collimated laser or microwave beam against a reflecting surface, the latter may be accelerated. The propulsion device, a laser (or maser) and its solar generator, located in space, may be used to launch several spacecrafts and needs not to be accelerated together with the probe, which can thus reach high speeds. The beam is much more concentrated than sun light and does not lose quickly its power with increasing distance from the Sun. Recently a number of experiments have been performed in which a small sail made of carbon-carbon microtruss fabric was accelerated in a vacuum chamber to several g by a microwave or a laser beam with a power of about 10 kW [13].

Laser and microwave sails may be structurally similar to solar sail, with usually larger thermal problems, owing to the higher energy concentration on their surface, and a smaller size, exactly for the same reason. Some control problems in keeping the sail within the beam may be encountered. If the sail is light enough, it is possible to design, at least in principle, very fast probes to perform true interstellar missions at relativistic speeds; the problem being only that of generating a powerful enough beam.

A beamed energy sail works best when the beam is reflected back by the surface. If the energy is absorbed, the direct thrust is smaller (half in the ideal absorption case if compared with the ideal reflection one) but the energy the spacecraft receives may be used to generate an additional thrust, i.e. by vaporizing some material and ejecting it. In this case it is possible to define a specific impulse for this part of the thrust.

5 ELECTRIC AND NUCLEAR THERMAL PROPULSION

Solar-electric propulsion, based on ion thrusters, has already been tested with success in space. However, to obtain a speed sufficient for an interstellar, although precursor, mission the source of energy must be a nuclear reactor, like the Russian *Topaz* or the American *SNAP* types which have already flown in space, even if reactors with higher power/weight ratio should be used for interstellar missions. Some difficulties are linked with the radiator, as for all power generating devices operating in space, but also here the problems are related more to improving performances than stating the feasibility. Ion engines which can work reliably for a time long enough must be developed; however what slows down this solution is not much the technological problems involved but the political issue related to the use of nuclear energy in space.

Ion and MPD (magnetoplasma dynamic) thrusters can operate with a specific impulse between 25,000 and 100,000 m/s, requiring a very high power/thrust ratio. A small nuclear reactor feeding ion engines is usually considered for robotic probes; however, if the probe is small, it may even be possible to use a radioisotope thermoelectric generator as a power source [14]: an RTG of the type used on the *Cassini* probe may already be used for small missions.

Nuclear thermal rockets can achieve a specific impulse of about 9,000-10,000 m/s, lower than that typical of electric thrusters, but can supply a thrust which is far larger. Again, the basics of nuclear propulsion are available and nuclear thermal rockets may be developed in a short time. Even by using a nuclear rocket of the type already tested on the ground in the *NERVA (Nuclear Engine for Rocket Vehicle Application)* project it will be possible to obtain good improvements with respect to chemical propulsion. If used together with gravity assist,

such propulsion devices allow to perform missions in the near interstellar space. Research is going on and several modern designs of solid-core rockets have been proposed (e.g. [15]), even if their main limitation is linked with the maximum allowable temperature of the core. Several designs of liquid (e.g. [16]) or gas core rockets have been introduced, with values of the specific impulse of about 20,000 or 45,000 m/s.

A proposal for a nuclear thermal engine in which the propellant gas is heated directly by the fission fragments has been recently forwarded by the Nobel laureate Carlo Rubbia. The proposal has been evaluated by the Italian Space Agency, particularly with reference to a manned mission to Mars (Project 242), and feasibility studies have been started. The advantages of the proposal lie in a high specific impulse together with high power density and small quantity of fissionable material (Americium 242) which is present in the engine.

In the opinion of the author, nuclear thermal propulsion is a need, not only to pursue the goals of interstellar space exploration, but also for reaching destinations which are closer to the Earth, such as Mars. In a sense, it could be paradoxically stated that nuclear propulsion is more important to travel within the boundaries of the solar system than for interstellar exploration, as it falls dramatically short for true interstellar exploration. But this is a paradox and the development of nuclear propulsion will stimulate those studies which will in the future lead to more advanced propulsion devices, as nuclear fusion engines or even more advanced ones.

6 NUCLEAR FUSION AND ANTIMATTER PROPULSION

Nuclear fusion propulsion (based on microexplosions or fully controlled fusion) involves quantities of energy far larger than those involved by fission and consequently allows to reach higher values of specific impulse, up to 1,000,000 m/s with high values of the thrust. Pulsed nuclear propulsion can in principle be achieved using present technologies. Its simplest form can be implemented by exploding small nuclear charges behind the vehicle; the products of the explosion impact a plate placed at its tail, pushing it forward at very high speeds. The Orion project, based on this principle (but on nuclear fission instead of fusion), was started in 1958; when the project was interrupted in 1965 a very detailed study had been performed, a final design had been done and a small rocket, in which the nuclear explosions had been substituted by small charges of a chemical explosive, had been flight tested. It stirred much enthusiasm and the proposers suggested that this propulsion method could allow to avoid completely the stage of chemical propulsion spaceflight to switch directly to interplanetary nuclear flight. The plan was to launch the first interplanetary nuclear spaceship in 1968.

The project was abandoned, as was later abandoned the Dedalus project, the first project for a very large interstellar probe based on nuclear fusion. Although the opposition to the use of microexplosions as a means of space propulsion seems to be more political than technological, at present there is little work going on along this line.

It seems that from many points of view it is easier to control nuclear fusion in a space engine than in a power station on the ground and the difficulties for building a fusion engine do not seem to be forbidding. Some designs suggest the use of small quantities of antimatter for starting the fusion reaction [17]; in this case very small quantities of antimatter are required, not much beyond present capabilities.

Antimatter propulsion is the ultimate propulsion method based on the emission of reaction mass: no known reaction can yield a larger amount of energy than antimatter-matter annihilation.

lation. The specific impulse can be very large, up to 20 million m/s, but the difficulties are at present so large that there is no way to predict whether and when this type of propulsion might become operational. The quantity of antimatter produced yearly at present is of about 1.5 ng, and its cost may be evaluated at 100 trillion US\$ per gram, making it the most expensive substance on the planet, not to mention the difficulties to store it.

However, antimatter and perhaps even nuclear fusion are even too advanced for interstellar precursor missions and are not really needed: when humankind will reach the stage in which it is able to control such phenomena, it will be ready for actual interstellar missions.

7 PROPULSION BASED ON NON CONVENTIONAL PHYSICS

At the end of the XIX century physics professors discouraged their best students from pursuing this discipline because all what matters ‘is already known’: such claims sound pathetic (and much arrogant) to us. It is just a matter of common sense and realism to be aware that our way toward the understanding of the Universe is just at its beginning and perhaps new discoveries will give us a new technology we now cannot yet even dream of and make our propulsion devices look obsolete. Even if there are not many hopes to reach quickly significant results, studies aimed to devise non-conventional propulsion means are under way; for instance *Breakthrough Propulsion Physics (BPP)* is a NASA programme funded within the Advanced Space Transportation Plan, aimed at the study of innovative concepts which could cause a true revolution in the very way in which we intend space propulsion and locomotion. As the project deals with concepts still at the stage of hypotheses, the work is focused more on the physical and mathematical aspects than on the applications: the point is to lay out the scientific foundations of what perhaps tomorrow could become technology [18]. A sentence which can be taken as the slogan of the project is *to perform credible progress toward incredible possibilities*.

However, the interest of these studies is limited in the context of precursor interstellar missions: their ambitions are far higher and, even if they will succeed, it is unlikely that the time needed to obtain such a new and revolutionary technology is compatible with the implementation of missions just beyond the orbits of the outer planets.

8 SPACECRAFT AND MISSION DESIGN

Some aspects of the global design of a mission and of the spacecraft must be dealt with while speaking of propulsion, as they affect it to the point of either allowing or making it impossible to perform a given mission with a given propulsion system.

Miniaturization is a key aspect of deep space missions, as everything gets simpler with the reduction of the payload mass. Microtechnologies and nanotechnologies will play a very important role; the point seems to be mostly a problem of development cost, which in space applications may be forbidding owing to the small scale production. A backward technology transfer, e.g. from automotive or biomedical field, may be worth considering: the complexity and performance of the solutions used in many automotive applications are astounding.

Another aspect is artificial intelligence, or perhaps the lack of it displayed by many interplanetary robots. In the context of the very deep space exploration it is no matter of discussing about the comparative merits of manned and robotic missions: at least in the near and medium term future no one can think of manned exploration in this area and also telepresence is to be

ruled out. Progress in the area of artificial intelligence seems to be slow, particularly if compared with that in the area of computer hardware: computers are increasingly faster and more powerful, but hardly smarter. What about if the ultimate problem of deep space exploration may not be propulsion but artificial intelligence (again, the lack of it)? If robots able to undertake this task will not be available, humans will have to go themselves, and this will require further, perhaps now unimaginable, progress in the propulsion field.

A final point which is important for deep space exploration is on-board power generation. As an interstellar probe must work at a large distance from the Sun or other stars, it cannot rely on solar panels. Up to now the use of RTGs has been widespread, but there have been political pressures against them, to the point of using solar panels on the Rosetta spacecraft. The situation can become a very severe one, particularly in Europe: what about having the probe, the propulsion system and everything else but not having the possibility of powering it?

9 CONCLUSIONS

The first precursor interstellar missions will be a very important step for humankind in its way to a larger world.

Present chemical propulsion devices are inadequate, even if combined with gravitational assist. Solar sails or solar electric (or even solar thermal) propulsion are important as “bridge” solutions, to achieve the goals of deep space exploration while more advanced propulsion devices are being developed. In particular, solar sails can allow to reach a few hundreds A.U. from the Earth in a reasonable time and to perform scientific missions in the near interstellar space. A precursor interstellar mission based on solar sailing can be planned for the near future without the need of long and very costly technology development studies.

As medium term solutions there are two viable alternatives: beamed energy sails and nuclear (thermal or electric) propulsion. The first one seems more adequate for small robotic probes while nuclear thermal propulsion has the capability of launching large payloads at high speed toward the interstellar space, being also suitable for manned missions within the solar system. Sample return missions from Kuiper belt objects require at least nuclear electric propulsion [19].

More advanced propulsion devices will eventually be contrived and will enlarge the range of human activity, but they are not essential for precursor interstellar missions. It would be a mistake to wait for them to be available to get out of the orbit of Neptune and set sails in the interstellar space.

As a last statement, it is opinion of the author that *if humankind wants to become an actual space faring species, it needs to pursue nuclear propulsion*. It will allow humans to explore personally the nearby parts of the solar system and through their robots the first reaches of interstellar space, while developing the technology needed to move on toward the stars.

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