Achieving the required mobility in the solar system through Direct Fusion Drive

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To develop a spacefaring civilization, humankind must develop technologies which enable safe, affordable and repeatable mobility through the solar system. One such technology is nuclear fusion propulsion which is at present under study mostly as a breakthrough toward the first interstellar probes. The aim of the present paper is to show that fusion drive is even more important in human planetary exploration and constitutes the natural solution to the problem of exploring and colonizing the solar system.

\textbf{Nomenclature}

\begin{align*}
I_s & \text{ specific impulse} \\
m & \text{ mass} \\
m_i & \text{ initial mass} \\
m_l & \text{ mass of payload} \\
m_p & \text{ mass of propellant} \\
m_s & \text{ structural mass} \\
m_t & \text{ mass of the thruster} \\
m_{\text{tank}} & \text{ mass of tanks} \\
t & \text{ time} \\
t_d & \text{ departure time} \\
v_e & \text{ ejection velocity} \\
F & \text{ thrust} \\
J & \text{ cost function} \\
P & \text{ power of the jet} \\
\alpha & \text{ specific mass of the generator} \\
\gamma & \text{ optimization parameter} \\
\Delta V & \text{ velocity increment} \\
DFD & \text{ Direct Fusion Drive} \\
IMLEO & \text{ Initial Mass in Low Earth Orbit} \\
LEO & \text{ Low Earth Orbit} \\
LMO & \text{ Low Mars Orbit} \\
NEP & \text{ Nuclear Electric Propulsion} \\
NTP & \text{ Nuclear Thermal Propulsion} \\
SEP & \text{ Solar Electric Propulsion} \\
SOI & \text{ Sphere of Influence} \\
VEV & \text{ Variable Ejection Velocity}
\end{align*}

I. INTRODUCTION

To develop a spacefaring civilization, humankind must develop technologies which enable safe, affordable and repeatable mobility through the solar system. Half a century ago (the last year we were celebrating the 50\textsuperscript{th} anniversary of the first human landing on the Moon) we have proven that the technology then (and today, since little has changed in this field in the last 50 years) available was barely sufficient to reach the closest celestial body, – the Moon, for a number of flag and footprint missions.
Although never yet attempted, it is possible to assess that the same technology can allow to perform some preliminary human missions to Mars [1][2].

Although it is well known that to really explore and colonize the closest celestial bodies a wide range of technologies need to be developed [3] – technology to exploit in-situ resources, to protect the astronauts from radiation, to build manufactures on the destination planet, etc. – new technologies directly related to propulsion are required. In particular, it is essential to use nuclear energy instead of chemical energy to propel spacecraft.

Both alternatives of Nuclear Thermal and of Nuclear Electric Propulsion (NTP and NEP) based on nuclear fission reactions have been studied in detail, and the former was already bench tested with very satisfactory results. NTP and NEP can allow to improve our chances of performing human missions to Mars and beyond by reducing the travel time (and thus the exposure of the crew to cosmic radiation) while at the same time reducing the Initial Mass in Low Earth Orbit (IMLEO) and thus making interplanetary missions more affordable. An interesting comparison between the NTP and chemical approach to a human Mars mission is reported in the NASA Design Reference Architecture 5 (DRA5) [3][4].

Also NEP allows a notable improvement with respect to chemical propulsion, and the choice between the two mentioned nuclear approaches depend mainly on political decisions about which technology to develop to a sufficient Technology Readiness Level. Both the mentioned nuclear approaches are based on fission nuclear reactions [3].

Recent advances in lightweight structures and thin film solar cells make it possible to think of using Solar Electric Propulsion (SEP) also for human planetary missions and in particular for the first human missions to Mars. This is a sort of 'bridge' solution to improve the performance of interplanetary spacecraft above those of chemical propulsion, while waiting that the technology for NTP or NEP becomes available. By comparing the performance of SEP with that of chemical propulsion and NTP, the advantages in terms of IMLEO are clear, while with respect to NEP they depend only on the specific mass of the generator \( \alpha \), which in the short term is more favorable for solar arrays than for nuclear generators. In a longer term, the latter will be much better, but developing SEP means developing high power electric thrusters for human missions so that they will be ready when lightweight nuclear generator will become available.

At any rate there is no doubt that to become a real spacefaring civilization we must develop rocket engines based on nuclear fusion [6][7]. The idea to use fusion power for spacecraft propulsion has a long history [8]. For the fusion propulsion there are two alternatives: similar to NTP and fusion NEP. In the last 20 years many studies have been devoted to the development of fusion nuclear power in general – mostly for general power generation – and specifically of fusion nuclear rockets. Fusion NEP requires the development of lightweight fusion reactors, which is something that today appears to be a difficult achievement. Moreover, also here the point is again just the specific mass of the generator \( \alpha \), and many years will pass before fusion generator will have a better value of \( \alpha \) than fission generators [9] – apart from the fact that today no fusion generator, even with a very high \( \alpha \), is available. In fusion NEP, the lower is the value of \( \alpha \), the higher is the optimum value of the specific impulse, so even when a lightweight generator will be available, much work will be required also for improving the electric thruster.

The revolutionary Direct Fusion Drive (DFD) is a nuclear fusion engine and its concept is based on the Princeton field-reversed configuration reactor, which has the ability to produce thrust from fusion without going through an intermediary electricity-generating step [10]. The DFD uses a novel magnetic confinement and heating system, fueled with a mixture of isotopes of helium and hydrogen nuclei, to produce a high specific power, variable thrust and specific impulse, and a low-radiation spacecraft propulsion system. The simplest type of fusion drive is using small uncontrolled thermonuclear explosions to push forward the spacecraft, as was planned in the Orion Project [5], but even if a continuous, controlled reaction is used, DFD seems to be much easier to realize and D – \(^3\)He direct fusion thrusters seem to be the thrusters which will allow to colonize, in the medium term, the solar system.

While most of the studies related to DFD deal with missions to the outer solar system or the near interstellar space, the aim of the present paper is studying in some detail fast human missions to Mars and to the Asteroid Belt. The result is that nuclear fusion propulsion is the enabling technology to start the colonization of the solar system and the creation of a solar system economy.

The paper is organized in the following way: In Section II we describe the thruster and its main characteristics. Section III is devoted to considerations of three cases for the Earth – Mars mission: i. the ideal variable ejection velocity (VEV) operations; ii. limited VEV operations; iii. slow cargo spacecraft mission. The mission to 16 Psyche asteroid is considered in Section IV, and finally conclusions
are given in Section V.

II. THE THRUSTER

The solar system exploration and beyond, from robotic space voyages to manned interplanetary missions, requires high-thrust, high-exhaust velocity engines. Our experience suggest that any engine engineered should be based on the well-understood physics of today. The emphasis on known physics and affordability limits the scope still further to nuclear processes: fission and fusion. However, both fission- and fusion-based propulsion schemes, are well understood and realizable at power levels, while at the same time the mass of fuel, propellant, structure, and shielding severely limit their space flight capabilities. A survey of rocket-engine performance for solar system missions beyond the Moon-Earth system has compared chemical and nuclear fission and fusion power sources [11]. One conclusion reached is that chemical rockets have reached their practical limits, epitomized by long-duration, low-payload-mass missions. A corollary is that nuclear power will be needed for more ambitious missions [12].

A nuclear fission reactor is used in a rocket design to create Nuclear Thermal Propulsion. In an NTP rocket the type of nuclear reactor, is ranging from a relatively simple solid core reactor up to a much more complicated but more efficient gas core reactor. The fission reactions are used to heat liquid hydrogen which flows around the fission region inside a reactor and absorbs energy from the fission products. High temperature heating turns liquid hydrogen into ionized hydrogen gas, which is then exhausted through a rocket nozzle to generate thrust. As an alternative, the propellant can be heated directly by the fission fragments, like in the thruster proposed by Carlo Rubbia [13]. The specific impulse produced is proportional to the square root of the temperature to which the working fluid is heated. The hydrogen propellant typically delivers specific impulses on the order of 850 to 1000 seconds, which is about twice that of liquid hydrogen-oxygen chemical rocket. A corollary is that electric specific impulse thrusters typically use much less propellant than chemical rockets because they have a higher. Therefore, in both cases, the rocket relies on nuclear fission to generate propulsion. The nuclear fission propulsion is limited by thermal inefficiencies and that fusion could provide more and better mission options because of its higher power conversion efficiency and higher energy-content fuel [11].

Fusion reactions produce much more energy than fission processes. Usually one of the components of the fusion reaction is protium (hydrogen atom without any neutron), deuterium (hydrogen atom with proton and neutron), or tritium (hydrogen atom with proton and two neutrons). The other component which involves into the fusion process of light nuclei can be deuterium, isotopes of helium, $^3$He or $^4$He, and isotopes of lithium, $^6$Li and $^7$Li. In fusion reactors use the energy released by the fusion of light atomic nuclei. Let us focus of the fusion processes in the deuterium–deuterium (D–D), deuterium–tritium (D–T) and deuterium–$^3$He (D–$^3$He) plasma.

The D–D plasma admits the following primary reactions:

$$D + D = \ ^3He (0.82 \text{ Mev}) + n (2.45 \text{ Mev}) + 3.25 \text{ MeV},$$

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In Eqs. (1) and (2) the values in parenthesis are the energy of that particular fusion product. The D–T plasma admits both deuterium–deuterium reactions (1) and (2) and deuterium–tritium processes. The primary energy reactions in the D–T plasma in addition to (1) and (2) are the following:

$$D + T = \ ^4He (3.52 \text{ Mev}) + n (14.06 \text{ Mev}) + 17.6 \text{ MeV},$$

$$T + T = \ ^4He (3.52 \text{ Mev}) + 2n + 11.3 \text{ MeV}.$$
the development of the plasma active isotopes and that initiates the emergence of important secondary catalytic processes $^3$ and $^4$.

However, the cross section for $^1$ and $^2$ reactions at low energies is considerably smaller than the cross-sections for the D–T process $^3$, and its ignition requires much higher temperatures of plasma. The ideal temperature threshold is $\approx 40$ keV (about $5 \times 10^8$ K).

The fusion reaction of nuclei of tritium and deuterium is the most promising for the implementation of controlled thermonuclear fusion, since its cross section even at low energies is sufficiently large $^{13}$. However, the problem of the contamination due to the neutron emission in the primary processes still exists. Although the D–D fuel burning is also accompanied by a neutron flux, they are weakened in comparison with the D–T process $^3$.

Now let us consider the reaction that are admitted in D–$^3$He plasma. The primary processes which occur in D–$^3$He plasma are the aneutronic fusion

$$D + ^3He = ^4He (3.52 \text{ Mev}) + p (14.7 \text{ Mev}) + 18.34 \text{ MeV}$$

and reactions $^1$ and $^2$ that involve the D–D fusion. One should mention that reaction $^5$ is the secondary process in the D–T plasma. Due to the D–D fusion, the D–$^3$He plasma also includes undesired neutron channel $^1$. The two branches of the D–D fusion reaction produce $^3$He and tritium. The only neutrons produced are medium-energy neutrons (2.45 MeV). If the produced $^3$He (Helium-3) is not removed, it will react with deuterium producing charged particles protons and $^4$He with no additional neutrons. On the other hand, if the produced tritium is not removed, it will react with deuterium producing 14.1 MeV neutrons. However for the D–$^3$He plasma with equal deuterium and Helium-3 densities, the fraction of the fusion energy carried by neutrons from the D–D reaction is $1/3$ $^{12, 13}$. The undesired tritium produced via reaction (2) will increase the neutron flux due to reactions $^3$ and $^4$, which are secondary for D–$^3$He plasma. In Refs. $^{10, 17}$ a method of tritium removal from the plasma before it can fuse has been proposed. Removing tritium produced by D–D fusion and recycling part of it after it decays to Helium-3 isotope significantly reduces the fraction of fusion energy carried by neutrons in a D–D system $^{17}$. The latter results in significant lifetime enhancement of structural materials. In summary, the main reactions in D–$^3$He fusion produce far fewer neutrons than D–D fusion. Consequently, a lower mass of shielding materials is required, which will reduce the total mass of the structure. Calculations show that for obtaining useful energy the temperature of ions in a plasma for the D + D reaction should be about $10^8$ K and for the D + T reaction about $10^8$ K $^{18}$.

The experimental study of the D–$^3$He plasma led to the proposal of a new kind the fusion-based thruster - the Direct Fusion Drive (DFD), which has field-reversed configuration (FRC) reactor for an original plasma-formation. The FRC employs a linear solenoidal magnetic-coil array for plasma confinement and operates at higher plasma pressures. One should note that several FRCs $^{19, 22}$ have achieved stable plasmas. The DFD employs the radiofrequency technique called rotating magnetic field (RMF) to form and heat plasma. An important figure-of-merit for fusion reactors is $\beta$, the ratio of the plasma pressure to the magnetic energy density. The innovative radiofrequency RMF method, which heats particles and allows the size of the FRC to be relatively small was suggested in Ref. $^{23}$. In Refs. $^{10, 12, 15, 24}$ was considered a compact, aneutronic fusion engine, which enables more challenging exploration missions in the solar system and beyond. The DFD concept is result of the Princeton Field-Reversed Configuration Reactors which employ heating method invented by S. Cohen. The Scrape-off Layer (SOL) of the DFD is quite different than that of any other fusion device. The energy is deposited in the SOL directly from the D–$^3$He fusion products via a non-local process and is predominantly transmitted to the electrons via fast-ion drag. The random thermal energy in the SOL electrons is transferred to the cool SOL ions through a double layer at the nozzle and via expansion downstream, thus being converted into directed flow of a propellant fluid. The heat transport into SOL is described by Fick’s law $^{25}$, by the local flux-surface-normal gradient in pressure. In Refs. $^{10, 26}$ is used a fluid model for the SOL between the gas box with the propellant and the nozzle and dependencies of the thrust and specific impulse on gas input flow for powers of 0.25 to 7 MW transferred to the SOL are studied. The calculations are performed using UEDGE $^{27}$ fluid-code for simulations. Results of these simulations for the propellant gas input 0.08 g/s yields to the data given in Table $^6$. The nuclear fuel for such a thruster is D–$^3$He and the propellant fluid is atomic or molecular deuterium, which is heated by the fusion products and then expanded into a magnetic nozzle, generating an exhaust velocity and thrust. Adding propellant to this flow results in a variable thrust, variable specific impulse exhaust through a magnetic nozzle. The thrust of the DFD depends on the input gas flow and varies from about 4 N for the power 0.25 MW to 60 N,
TABLE I: DFD propulsion parameters based on UEDGE Model spacecraft based on the DFD studies in Refs. [10, 26, 35].

| Parameter                  | Value     |
|----------------------------|-----------|
| Total Fusion Power, MW     | 1         |
| Specific Impulse, \( I_s \), s | 10,000    |
| Thrust, \( T \), N         | 8         |
| Fusion Efficiency          | 0.17 – 0.46 |
| Specific Power, kW/kg      | 0.75 – 1.25 |

when the power is 7 MW. The results of simulations show that when the gas input flow increases from 0.08 to 0.7 g/s the thrust increases from 4 N to 60 N. For the specific impulse the preferable gas feed for the power 0.25 MW to 7 MW is 0.08 – 0.3 g/s [10, 26]. Approximately 35% of the fusion power goes to the thrust, 30% to electric power, station keeping and communication, 25% lost to heat, and 10% is recirculated for the radio frequency heating. The current estimated DFD specific powers are between 0.3 and 1.5 kW/kg [10]. One could considered as a conservative estimate the power to thrust efficiency, about 0.3 – 0.5.

A full-sized D–\(^3\)He fusion reactor is perfectly suited to use as a rocket engine for two reasons:

i. the configuration results in a radical reduction of neutron production compared to other D–\(^3\)He approaches;

ii. the reactor features an axial flow of cool plasma to absorb the energy of the fusion products.

In other words, the cool plasma flows around the fusion region, absorbs energy from the fusion products, and then is accelerated by a magnetic nozzle.

The ratio of the total mass of fuel and propellant to the mass of \(^3\)He is about 670 and to get a specific power 0.18 kW/kg the small amount of \(^3\)He is needed – about 0.53 kg. The most Helium-3 used in industry today is produced from the radioactive decay of tritium. Tritium is a critical component of nuclear weapons and it was produced and stockpiled primarily for this. At present, Helium-3 is only produced as a byproduct of the manufacture and purification of tritium for use in nuclear weapons. The main source of Helium-3 in the United States is the federal government’s nuclear weapons program [28]. There are extraterrestrial sources of \(^3\)He. Materials on the Moon’s surface which contains Helium-3 at concentrations between 1.4 and 50 parts-per-billion in sunlit and shadowed areas [29–31]. There is may be Helium-3 on Mars also [32]. The analysis of fusion fuel resource base of our solar system is given in Ref. [33].

A spacecraft driven by a fusion thruster was studied at the turn of the century by NASA: its goal was to perform a human mission to Jupiter or Saturn as described in the Movie 2001, a Space Odyssey. The spacecraft was aptly named Discovery II [34]. The main characteristics of the thruster (in the version for the Saturn mission) which were obtained in that study were: specific impulse \( I_s = 47,205 \) s and specific mass of the propulsion system \( \alpha = 0.00016 \) kg/W and are listed in Table I. These values are very favorable indeed. DFD, with a specific impulse in the range of 10,000 to 20,000 seconds and a specific power about 1 kW/kg, is suitable for almost any interplanetary mission. In NASA solicitation for rapid, deep space propulsion, four candidate missions were identified: Mars, Jupiter, Pluto, and 125 AU for an interstellar precursor mission. In Ref. [35] has sized a DFD engine for each candidate mission. The main characteristics of the spacecraft are reported in Table I. A more recent study for a DFD driven spacecraft is reported in Ref. [10]. Although showing a small spacecraft aimed at the focal line of the gravitational

TABLE II: Main characteristics of the Discovery II and a spacecraft based on the DFD thruster studied in Ref. [10].

| Parameter                  | Value     |
|----------------------------|-----------|
| Specific impulse \( I_s \), s | 47,205    |
| Specific mass of the propulsion system \( \alpha \), kg/W | 0.000116    | 0.0018 |
lens of the Sun and an interstellar probe aimed at Alpha Centauri, the basic values there reported for a 2 MW fusion rocket can be considered as a conservative estimate for a larger unit aimed to power an interplanetary piloted spacecraft.

III. EARTH – MARS MISSION

A. Ideal Variable Ejection Velocity operations

In our consideration of the Earth – Mars mission we use the parameters for the DFD thruster given in Table II. As it was shown by the authors in a previous paper [36], a thruster with such a high specific impulse and low specific mass must operate in a continuous thrust mode. A first study of an Earth-Mars transfer was performed assuming that it can operate in an optimal (unlimited) Variable Ejection Velocity (VEV) conditions. The study was performed using the IRMA 7.1 computer code [37] with the following data: launch opportunity: 2037; specific mass $\alpha = 1.25$ kg/kW; overall efficiency $\eta = 0.56$; tankage factor $k_{tank} = 0.10$; height of circular starting LEO: 600 km; height of circular arrival LMO: 300 km.

The optimal trajectory for a 120 days Earth-Mars journey starts 66.6 days before opposition, spends 8.4 days spiraling about Earth, 105.8 days in interplanetary space and finally 8.4 days spiraling about Mars to reach the final LMO. The mass breakdown and the jet power are reported in Table III second column.

Notice that the ratio between the installed power and the vehicle mass is of the order of magnitude of that of a modern small car, showing that traveling fast in the solar system does not require enormous amounts of power!

The optimum specific impulse is shown in Fig. 1. The specific impulse ranges between 1,790 s at start and 60,250 s at midcourse, which is 60 days after starting.

B. Limited Variable Ejection Velocity operations

The minimum and the maximum values of the specific impulse are certainly beyond the possibilities of the thruster, so the computation was repeated limiting the specific impulse between 9,900 and 12,000 s. In this case the optimal strategy is increasing the duration of the planetocentric phases (the specific impulse is higher than the optimal one in these phases, and keeping their duration at the optimal value of the unlimited case would result in an unacceptable increase of the jet power) and introducing a coast arc at the interplanetary mid course, introducing a bang-bang regulation of the thruster.

The orbit-to-orbit bacon plot is reported in Fig. 2 at equal transfer time the payload mass fraction is slightly lower and thus to maintain the same payload fraction a slightly longer travel time has to be accepted.

| Table III: Timing and mass breakdown of the missions studied in the present paper. |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Destination Type | Unlimited | Mars | Limited fast | Limited cargo | Psyche |
| $t_d$ (days) | 66.6 | 71.9 | 189.9 | 120 |
| $t_1$ (days) | 120 | 123 | 350 | 250 |
| $t_3$ (days) | 8.4 | 20.6 | 94.5 | 27.6 |
| $t_2$ (days) | 105.8 | 96.0 | 219.2 | 222.3 |
| $t_3$ (days) | 5.8 | 6.4 | 36.3 | 0.1 |
| $(m_{t} + m_s)/m_i$ | 0.254 | 0.258 | 0.715 | 0.241 |
| $m_p/m_i$ | 0.525 | 0.319 | 0.178 | 0.416 |
| $m_t/m_i$ | 0.169 | 0.391 | 0.089 | 0.169 |
| $m_{tank}/m_i$ | 0.052 | 0.0319 | 0.018 | 0.042 |
| $P_{jet}/m_i$ (W/kg) | 75.62 | 175.35 | 40.09 | 134.60 |
A slightly longer transfer time, \( t_t = 123 \) days, is chosen. The trajectory starts 71.9 days before opposition. The mass breakdown and the jet power are reported in Table III, third column. The trajectory is shown in Fig. 3 while the time histories of the acceleration, the ejection velocity, the thrust and the power of the jet are shown in Fig. 4.

The limitation of the minimum exhaust velocity reduces the propellant consumption but causes an increase of the installed power and thus of the mass of the thruster. The overall result is a decrease of the payload mass at equal total journey time.

C. Slow cargo spacecraft

A slow cargo ship able to carry to Mars large payloads in an inexpensive way can also be built with this technology. Assuming a travel time of almost one year (namely 350 days) and starting from Earth orbit about 190 days before the opposition, the results reported in in Table III, fourth column are obtained. The payload and structures mass fraction is quite high, above 70% (namely 0.715), which means that
using a single superheavy launcher able to carry 130 t in LEO, a cargo of about 93 t (minus the structural mass) can be carried into LMO.

Also the power of the jet is quite small, of about 40 W/kg (referred to the IMLEO).
IV. MISSION TO 16 PSYCHE ASTEROID

Asteroid 16 Psyche, which belongs to the asteroid belt, is a metal asteroid extremely rich in nickel and iron, but also in gold. NASA plans a mission to survey this asteroid which should be launched in August of 2022, and arrive at the asteroid in early 2026, following a Mars gravity assist in 2023. The asteroid has a mass of $1.7 \times 10^{19}$ kg and an average diameter of 226 km.

Using the DFD thruster here described a mission to the same asteroid can be performed in a quite short time: for instance, using the launch opportunity of 2037 (the opposition is on March 4, 2037) and starting 120 days before the opposition, a mission lasting only 220 days can be performed. This figure must be compared with the roughly 3.5 years of the mentioned NASA proposal, based on chemical propulsion and gravity assist. The mass breakdown and the jet power are reported in Table III last column.

![Trajectory for a 250 days journey to the metal asteroid 16 Psyche.](image)

The payload and structure fraction is quite high (0.241) and the travel time is low enough to imagine even a human mission to a metal asteroid of the main belt like 16 Psyche – since the planetocentric part of the trajectory lasts almost one month, a human mission in which the astronauts reach the spacecraft at the exit from the earth sphere of influence would last about 225 days, roughly like most of the human Mars missions presently planned.

V. CONCLUSIONS

From the study here performed it is clear that the development of a nuclear fusion rocket engine based on the D-$^3$He technology will allow to travel in the solar system with an ease never before attained, opening almost ‘science fiction’ possibilities to humankind.

One way travels to Mars in slightly more than 100 days become possible and also journeys to the asteroid belt in about 250 days After the return to Earth orbit the spacecraft can be refitted and refurbished to make another travel in the following launch opportunity: a sort of commuting Earth-Mars service aimed at the colonization of the red planet. A spacecraft able to carry 30 t in 120 days or 85 t in 350 days to Mars may be launched from the Earth surface with a single superheavy-lift launcher (slightly bigger than the Saturn 5 or the Energia). A cargo ship able to carry to LMO the propellant required for the return journey and much cargo is also possible.

However, the performance of such devices is still hypothetical and the value of its specific mass here assumed is conservative also taking in mind that this technology has very ample margins for improvements – as an alternative to chemical propulsion which has already reached the limits of this technology. If
a lower value of the specific mass (a higher value of the specific impulse) will prove to be feasible, even faster interplanetary spacecraft could become possible.

The spacecraft described in the present paper still require much research and development, but it is possible that they become feasible in less than two or three decades (the launch opportunity here studied is that of 2037, – 17 years from now), which is a fairly favorable one for Mars, while, on the contrary is not a very good one for 16 Psyche however with such powerful spacecraft the difference between a ‘good’ and a ‘bad’ launch opportunity is smaller than when using chemical propulsion.

If a DFD could be made available in time for the first human Mars missions – as the launch opportunity here chosen implicitly implies –, the latter would become much easier, safer and affordable than what is today thought. These results show that the development of this technology should be given a high priority by space agencies and public and private research centers.

Today chemical propulsion technologies are available to make a Mars mission possible and the foundation of fusion propulsion is already being built. However, it could be a fusion-powered spacecraft that ferries us to Mars in foreseeable future. We should believe that by mid-21st century, trips to Mars may become as routine as trips to the International Space Station today due to achievements in developments of fusion-powered thrusters.

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