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Combining magnetic and electric sails for interstellar deceleration

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ABSTRACT

The main benefit of an interstellar mission is to carry out in situ measurements within a target star system. To allow for extended in situ measurements, the spacecraft needs to be decelerated. One of the currently most promising technologies for deceleration is the magnetic sail which uses the deflection of interstellar matter via a magnetic field to decelerate the spacecraft. However, while the magnetic sail is very efficient at high velocities, its performance decreases with lower speeds. This leads to deceleration durations of several decades depending on the spacecraft mass. Within the context of Project Dragonfly, initiated by the Initiative of Interstellar Studies (i4is), this paper proposes a novel concept for decelerating a spacecraft on an interstellar mission by combining a magnetic sail with an electric sail. Combining the sails compensates for each technology's shortcomings: a magnetic sail is more effective at higher velocities than the electric sail, whereas an electric sail demonstrates superior performance at low speeds. It is shown that using both sails sequentially outperforms using only the magnetic or electric sail for various mission scenarios and velocity ranges, at a constant total spacecraft mass. For example, for decelerating from 5% c, to interplanetary velocities, a spacecraft with both sails needs about 29 years, whereas the electric sail alone would take 35 years and the magnetic sail about 40 years with a total spacecraft mass of 8250 kg. Furthermore, it is assessed how the combined deceleration system affects the optimal overall mission architecture for different spacecraft masses and cruising speeds. Future work would investigate how operating both systems in parallel instead of sequentially would affect its performance. Moreover, uncertainties in the density of interstellar matter and sail properties need to be explored.

1. Introduction

The concept of manned and unmanned interstellar missions has been examined in different contexts by many authors within the past decades [1]. The main obstacle connected to the design of such a mission is the necessity for an advanced propulsion system which is able to accelerate the spacecraft towards the target system within a reasonable time span. To overcome the vast interstellar distances, propulsion systems with high specific impulses, like the fusion based engines in the ICARUS and Daedalus projects have been proposed [2,3]. Other methods rely on propellant-less systems like laser-powered light sails, as described in [4].

Accelerating a probe to high speeds and reaching the target system within short duration using advanced propulsion systems would be a big achievement for mankind. However, the scientific gain of an interstellar mission would be immensely increased with an extensive scientific payload. In order to produce valuable scientific results, the deceleration of the probe is required since it enables the study of star and planetary systems in detail [5]. For a more detailed analysis of exoplanets, involving surface operations, a deceleration down to orbital speeds is necessary.

Therefore, apart from the acceleration propulsion system, a further crucial mission component which is often overlooked, is the deceleration system of an interstellar mission. This has to demonstrate equally effective Δv capabilities as the propulsion system. For that reason, methods utilizing propellant are not preferred, since they would induce large amounts of mass, which are inert during the acceleration and cruising phases of the mission.

Two attractive concepts rely on utilizing magnetic and electric fields in order to deflect incoming ions of the interstellar space and thereby decelerate effectively. These systems called *Magnetic Sail* (*Msail*) and *Electric Sail* (*Esail*) were first proposed by Zubrin and Andrews [6] and Janhunen [7] respectively. Since each one of those systems has a different design point and velocity application regime in which it performs optimally, the combination of the two can induce great flexibility in the mission design as well as better

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performance.

To demonstrate these points, the example of a mission to Alpha Centauri is analyzed. This star system was chosen because it is the closest one to the earth at a distance of 4.35 light years and because it is the target system of the Dragonfly Competition, organized by the i4is [8]. The concept of the Dragonfly mission involves sending a scientific payload to the nearest star system within a century from its launch, using a laser-powered light sail for the acceleration part of the mission. Within the framework of this mission, the requirement of deceleration is formulated, in order to increase the scientific yield of the payload operations in Alpha Centauri, however no concrete deceleration method has been prescribed.

The combination of Msail and Esail is proposed by the authors of the present paper as an effective deceleration method for the Dragonfly mission. The starting point for the design of the system was hence the mission profile of the Dragonly project. However, this deceleration system appears to be scalable with respect to the spacecraft mass (as described in Section 6) and can be therefore examined independently from the Dragonfly mission. It can serve as a modular component in the design of an interstellar mission, decoupled from the acceleration propulsion system. For that reason, the authors propose it not only as a braking system for the Dragonfly mission but also as a replacement for pure magnetic or electric deceleration in interstellar missions with arbitrary primary propulsion system (fusion, antimatter or laser-powered sail).

2. Sail properties

Before the comparison of the different deceleration methods takes place, the properties of each sail will be shortly analyzed and the assumptions used in the simulation of their performance will be explained.

2.1. Magnetic sail (Msail)

The Msail consists of a superconducting coil and support tethers which connect it to the spacecraft and transfer the forces onto the main structure. The current through the coil produces a magnetic field. When the spacecraft has a non-zero velocity, the stationary ions of the interstellar medium are moving towards the sail in its own reference frame. The interaction of ions with the magnetosphere of the coil leads to a momentum exchange and a force on the sail, along the direction of the incoming charged particles.

The force on the sail is calculated according to the following equation [9]:

$$F_{Msail} = 0.345\pi\left(m_p n_o \mu^{0.5} I R^2 v^2\right)^{3/2} \tag{1}$$

where m_p is the mass of the proton, n_o is the number density of interstellar ions, μ is the free space permeability, I is the current through the sail, R is its radius and v is its speed. Values for n_o are proposed in [10] in the case of a space probe traveling to Alpha Centauri. In this work, a rather conservative value was implemented, with $n_o = 0.03\ \text{cm}^{-3}$ corresponding to the expected values in the Local Bubble [10].

The main structural component introducing extra mass into the system is the sail itself, as well as its shielding and its deployment mechanism. The mass of the sail is defined by the maximal current density that can be achieved with the superconducting material, since this dictates the minimal cross sectional area for a specific current. According to Zubrin and Andrews [6], the current densities of superconductors can reach up to $j_{max} = 2\cdot 10^{10}\ \text{A/m}^2$ and this is the value used in the analysis. For the material of the sail, the density of common superconductors like copper oxide (CuO) and YBCO was used, with $\rho_{Msail} = 6000\ \text{kg/m}^3$.

The shielding mass required to protect the sail was modeled according to [3]. This mass vaporizes due to collisions with interstellar atoms and ions and the total mass vaporized after time T is given by the following equations:

$$m_{shield} = \int_0^T \frac{\mathrm{d}m_{shield}}{\mathrm{d}t}\mathrm{d}t \tag{2}$$

$$\frac{\mathrm{d}m_{shield}}{\mathrm{d}t} = \frac{A_{ion} m_p n_o}{\Delta H}\frac{\beta c^3}{\sqrt{1-\beta^2}}\left[\frac{1}{\sqrt{1-\beta^2}} - 1\right] \tag{3}$$

In Eq. (3), A_{ion} represents the cross sectional area of the coil, as seen from the direction of the incoming ions, ΔH is the vaporization enthalpy of the shielding material and $\beta = v/c$. Graphite was chosen as a shielding material since it combines a low density with high vaporization enthalpy. The shielding mass is calculated separately for each configuration, since its calculation requires knowledge of the time-dependent profile for β. For that reason, its calculation is carried out with an iterative procedure.

For the tether and support structures, a mass equal to 15% of the sail mass was used.

It is evident from the formula in Eq. (1) that the magnetic sail is efficient for higher current values and larger dimensions. In the analyses presented in this work, the radius of the Msail was limited to 50 km. Although even larger dimensions can demonstrate better performance, it was thought that the deployment of bigger radii is far from the current or near-future technological capabilities and was therefore excluded from the analyses.

The main disadvantage of the magnetic sail is also evident when taking the force formula into account. At lower speeds, the force keeps getting reduced asymptotically, and hence the effect of the Msail at these velocities becomes negligible. This has as a consequence that reaching orbital speeds (10–100 km/s) requires long deceleration duration. A magnetic sail would therefore be optimal for missions where no orbital insertion or surface operations in planetary systems are required but where a deceleration for prolonged measurements in the target system is sufficient. Its inefficiency in lower speeds indicates the need for a secondary system able to bring the velocity down to orbital values.

2.2. Electric sail (Esail)

Similar to the Msail, where a magnetic field deflects incoming ions, the Esail uses an electric field to change the trajectories of the interstellar protons. The sail consists of extended tethers which are charged with a high positive voltage.

The force on the Esail demonstrates a more complex dependency on the velocity compared to the Msail. The force can be described by the following equation [11]:

$$F_{Esail} = NL\frac{3.09\cdot m_p n_o v^2 r_o}{\sqrt{\exp\left(\frac{m_p v^2}{eV_o}\ln\left(\frac{r_o}{r_w}\right)\right) - 1}} \tag{4}$$

with N standing for the number of tethers, L their length, V_o the voltage of the sail, e the charge of the electron, r_w the wire radius and r_o the double Debye length λ_D, given by the following equation:

$$r_o = 2\lambda_D = 2\sqrt{\frac{\epsilon_o k_b T_e}{n_o e^2}} \tag{5}$$

In the Debye length definition, ϵ_o is the electric permittivity of