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A CRITICAL REVIEW ON THE VIABILITY OF A SPACE PROPULSION BASED ON THE SOLAR WIND MOMENTUM FLUX

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Abstract—In this paper three major aspects of the magnetic sail propulsion concept are critically reviewed. Two of them concern spacecraft technology in relation to large superconducting devices onboard. The third is concerned with the real physics of the interaction between the solar wind and the magnetic spacecraft. It is pointed out that technological difficulties, although considerable, do not appear insurmountable. In contrast, much work has to be done to understand the important aspects of the interaction mode by which the spacecraft would be thrusted. In any case, the strong solar wind fluctuations cannot be ignored and may render this potential propulsion mode impracticable in the solar system.

1. INTRODUCTION

The Sun is a powerful source of photons and charged particles. It is reasonable to try to utilize either or both these sources to travel between distant points or bodies in space. By the former source one would have a conventional solar sail drive, by the latter source one would realize a magnetic sail flight. This non-conventional concept of sail propulsion based on magnetic field was proposed by Andrews and Zubrin in 1988[1]. Since then other papers investigating many aspects of the magnetic sail have appeared in the specialized literature[2–7]. Recently, Matloff and Cassenti[8] have suggested collection of the very rare ^{3}He nuclei from the solar wind. Magnetic fields have also been proposed to shield manned spaceships[9]. These last two concepts, obviously, are not related to propulsion. However, all have some common problems to be clarified.

The solar wind originates from holes in the solar corona and consists mainly of protons and electrons. Charged particles are accelerated inside a region roughly spherical in shape; its radius extends about 20 solar radii. Observations indicate that the solar wind moves in a radial direction from the Sun at essentially any distance. Both density and speed depend, at the same distance, on the solar latitude. In the ecliptic plane and at 1 AU the mean density of the quiet solar wind is about 10×10^{-21} kg/m^3 (or 6 protons/cm^3), whereas the mean speed amounts to 400 km/s. Thus, the solar wind dynamic pressure or momentum flux (which is twice the kinetic energy density) is 1.6×10^{-9} N/m^2. Non-radial components in the ecliptic or normal-to-ecliptic components of the solar wind contribute about 0.3% of the radial pressure[10]. They therefore can be neglected from a propulsion point of view together with a number of other effects, though they are important for plasma physics in the solar system. On the other hand, at 1 AU the solar photon flux, averaged in one year, is 1358 W/m^2; then, the related pressure amounts to about 4.53×10^{-6} N/m^2, or about 2800 times the solar wind pressure. This means that it is not possible to exploit the solar wind dynamic pressure by a material sail that the charged particles would impinge. The ensuing thrust acceleration would be incredibly low, even for ultra light materials. The only way to get a reasonable acceleration is to make the sail by some field, which should have the further advantage of extending much beyond the geometric sizes of its source. The magnetic field satisfies these features (albeit one cannot strictly refer to *a sail* in this case, but to an interaction volume). How would a magnetic sail work? In principle, a current loop may be sufficient to generate an extended magnetic field which in some way would reflect or deflect the charged particles of the solar wind, thus producing a thrust on the space vehicle anchored to the loop by cables. There are a number of problems to be clarified and solved before such a spacecraft may be realized, of course. However, there are three major problems:

(a) the source of the magnetic field;
(b) the integrated energy required by the magnetic field;
(c) the interaction between the solar wind and the magnetic field generated by the spacecraft.

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Strange enough, problem (c) (which should be a clear step) has somehow been underestimated hitherto, although two models have been considered. We will discuss this point in Section 4.

2. MAGNETIC SAIL FIELD SOURCE

The magnetic energy density the spacecraft should generate has to be greater than the kinetic energy density of the solar wind (as seen from the spacecraft) to efficaciously change the local wind momentum. The following points are to be considered for this purpose:

(1) an electric circuit composed of a low number of circular rings as a current source,
(2) a plasma–sail interaction cross area at least 3000 that of a photon sail area (otherwise there would be no dynamical advantage with respect to a conventional solar sail of the same mass).
(3) the overall mass of the loop and cable system is higher than the other spacecraft systems.

Then, wire loops 50–100 km in radius have to host electric currents ranging from some hundreds to many thousands of amperes, depending on the thrust to gravitational acceleration ratio that one needs for a certain mission[1–7]. By some analogy to the light number defined for a solar photon sail, we may refer to the above ratio as the wind number. Different from the light number that keeps practically constant, if the photon sail attitude does not change along the flight, the wind number should vary significantly even in the pure radial motion at constant magnetic sail attitude. In any case, the initial value of the wind number should be greater than one for a fast mission in the solar system. The related electric currents should persist for years. These figures show that only superconductors shall be used for a magnetic sail. About such a point two lines of thought have been followed by investigators[1–7]:

(i) high-temperature superconductors;
(ii) conventional superconductors.

The discovery of superconducting materials (such as $YBa_2Cu_3O_7$, often denoted by YBCO) at temperatures in the 77–120 K range has inspired many high-performance potential applications. Space propulsion is one of them. However, efficient applications require high magnetic fields, from a few teslas to tens of teslas in some cases. Superconducting long coils of appropriate shape should exhibit a high, approximately uniform field inside them. High-current large-radius loops (such as those necessary for a magnetic sail) have to work under high magnetic field close to the wire surface only (the field decays rapidly as distance increases). However, the superconducting wire's working temperature is strongly affected by the magnetic field according to the superconductor's *critical surface*, namely the basic relationship between critical temperature, critical current density and critical magnetic induction. High-temperature materials would be the ideal solution even for the magnetic sail. There would be no need to arrange a complex screen (such as an additional solar sail) against the solar light to achieve the temperature allowing the loop to sustain the mentioned high currents. Unfortunately, high magnetic inductions of 5–10 T can cause transition from the normal to the superconducting state at a temperature down to one third of the no-field temperature. In addition, in the presence of an intense field, phenomena such as the vortex glass phase (which is rarely observed in low-temperature superconductors), the flux creep and the thermal vortex-line fluctuations[11–15] ultimately reduce the transport electric currents in *dirty* superconducting alloys, namely, just those of technological interest. Although some small electronic devices based on high-temperature superconducting films, have been successfully set up, unfortunately we are still far from the mature status of low-temperature superconductor (for instance, the NbTi alloy) technology which is able to produce many more kilometres of wire and at low cost too (< $1000/km). Some examples from [16] can help us to clarify this difficulty. At the time of this writing a European collaboration was about to start a program with the goal of building a YBCO wire 0.25–0.5 mm in radius (or equivalent geometry), at least 10 m long at 77 K with uniform superconduction properties (*texture*) and under a field of 0.5 T. It is hoped to obtain a current density of 20 A/mm^2 (to compare with over 10,000 A/mm^2 of NbTi). A research group of the Japanese Sumitomo has built a Bi-2223 wire as long as 250 m at 77 K. But the related texture is very poor: 470 A/mm^2 for few centimetres and with no field. In the presence of a 1-T field the current density falls to 50 A/mm^2. Under the same field the Fujikura has obtained 700 A/mm^2 in a 77-K YBCO wire, but 18 mm long! Everyone hopes that considerable improvement will be achieved in a few years. Problems to be solved are considerable and the proper way may only be found, if any, when a better theory on the high-T superconduction phenomena is set up. Reference [6] analyses, to a certain extent, the conventional superconductors as a field source for magnetic sail. It seems possible to be able to use long low-temperature (in the range 4.5–6 K) superconducting wires in space. However, the technological complexity would increase considerably due to the photon sail ring which has to prevent the superconducting loop from being exposed directly to the solar light. Considering an extra solar mission aimed at the heliopause, this screen is surely necessary for Sun–spacecraft distances less than 20 AU, where the vehicle achieves about 90% of its final speed.

3. MAGNETIC SAIL ENERGY SOURCE

The high values of superconducting current circulating in a number of multi-wire large loops (that is, of a high self-inductance coefficient), according to the figures given in Section 2, entail a dedicated onboard energy source that has to charge the superconductor. The charging process may be one of those used on the ground. However, this process must take place almost impulsively, namely, the superconducting working current has to be achieved in a few seconds, otherwise the resistive losses of the charging circuit become prohibitive. This means installing an onboard quasi-impulsive discharge device to charge the superconducting circuit. This may be a suitable series–parallel capacitor bank the specific mass of which should not be greater than a few tons/MJ. All these aspects were dealt with in [6]. Here we point out that more than one charging process may be necessary if the superconductor quenches. This would entail a spacecraft with a few-kWe nuclear reactor primarily aimed at feeding the discharging device as many times as needed.

4. WIND–SAIL INTERACTION

In the last three decades considerable advances have taken place in the knowledge of the physics of the solar system plasma and its interaction with the planets. Theory and observations from interplanetary and planetary probes have paced parallely [17–24 and references therein]. Since the seventies the dissipationless MagnetoHydroDynamics (MHD) has succeeded in progressively describing the solar wind properties modified by the solar system bodies, in particular around the planets with an intrinsic magnetic field. In fact, the solar wind is an expanding momentum-dominated high-conductivity super-alfvénic (pseudo-)supersonic collisionless plasma for which a *continuum* description, such as the MHD, amazingly applies very well and past the planets too. However, at present the MHD applicability range is not known. MHD is certainly valid for the many-thousand-kilometre objects the solar wind collides with. What happens when an object of 50–100 km, such as a fast magnetic-sail spacecraft, intercepts the solar plasma? Which description (the fluid or the particle one) holds for their interaction? In the latter case [1] the magnetic sail would act as a non-dipole magnetic field lens and would reflect almost all charged particles provided its magnetic field is sufficiently high. In the MHD case (only slightly considered in [1–7]), a Magnetosheath (MS) with a Bow Shock (BS) and a MagnetoPause (MP) as boundaries would be expected. The BS diverts, heats and slows down the solar wind. The flow becomes subsonic close to the MS nose, gradually becomes supersonic again, then restores the interplanetary conditions far behind the obstacle. The interplanetary magnetic field (transported by the solar wind) plays a role in the MS, whereas the spacecraft field is compressed inside the MP. On the MP the magnetic pressure of the spacecraft field balances the total solar-plasma pressure. All this is in analogy with the magnetic planets. However, there are three main aspects particularly important for spacecraft dynamics.

First, the solar wind dynamic pressure may change up to a factor 1600 or more at any fixed distance R from the Sun. Alternating beams of low-speed and high-speed solar winds emanate from the solar corona. They interact with each other and, if their speed difference is sufficiently high, can cause a pair of shocks corotating with the Sun. The pressure gradients generated in such shocks provoke non-radial flows. These high-speed particles form *fast streams*, which overlap almost periodically on the *quiet* ambient low-speed wind. The ambient solar wind exhibits a mean speed of 400 km/s and a number density of 5–7 protons/cm^3 at 1 AU. In contrast, the fast streams are characterized by a time-averaged mean speed and number density up to 600–700 km/s and 50 protons/cm^3, respectively, at 1 AU. Lower (down to less than 250 km/s and 1 proton/cm^3) or higher (up to more than 1000 km/s and 100 proton/cm^3) values of speed and density, respectively, have been measured in exceptional events. The solar wind speed also depends on the heliomagnetic latitude. It has been found that the solar wind reaches a minimum close to the interplanetary current sheet, whereas it augments with the latitude both above and below the sheet. Temperature decreases as R increases. At 1 AU the ion temperature floats in the 10^4–10^5 K range. All this means that the thrust acting on the spacecraft changes considerably, although one would expect that it may depend on the less-than-one power of the solar pressure [6].

Second, the solar wind number density decreases with R^{-2}. This may provoke an interaction mode transition as the spacecraft increases its distance from the Sun. In other words, if the vehicle saw the solar wind as a fluid at a few AUs, it may sense the wind as particles from a certain distance on. What is this critical R, say R_c? One needs to compute R_c because thereafter thrust might change considerably.

Third, a magnetic sail spacecraft should go much faster than a planet and in a radial direction too for distant-target missions. This means that the BS and MP characteristics change rapidly with time because the solar wind pressure—as seen in the spacecraft frame—decreases as the probe moves outwards.

We have to point out that the range of applicability of MHD entails a set of conditions not well known so far. If one uses criteria based on the general plasma parameters (Debye length, skin depth, gyration radius, etc) for the solar wind at scales down to some tens of kilometres, the risk of rough mistakes is high. In addition, in the last decade careful investigations have shown that the physics of magnetopause is much more complex than the bulk property described above.

5. CONCLUSIONS

Apart from the difficulty in computing the instantaneous thrust on a magnetic-sail vehicle, the considerations made in Section 4 tell us that the trajectory of such a spacecraft is quite stochastic, even in the case of a magnetic-lens interaction mode. If the mission purpose is to rapidly escape from the solar system, then the uncertainty in the flight design might have a relatively smaller impact on the mission. However, both navigation and guidance will be hard to manage when the source of propulsion is highly uncertain and quite out of human control. As a consequence, we do not see any reliable application to a planetary mission as proposed in [2]. In contrast, one could become confident that the technological problems described in Sections 2 and 3, although of significant difficulty, may be solved. In any case, before concluding that the somewhat intriguing magnetic-sail propulsion is infeasible, further detailed studies should be performed. They should assess not only the type of interaction with the solar wind in a broad interval of distances from the Sun, but also try to find out a *damping* solution to the thrust variability. Perhaps some variable sail arrangement able to adjust the thrust without consuming too much energy onboard might result in a feasible spacecraft.

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