Applications of the Electrodynamic Tether to Interstellar Travel

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ABSTRACT: After considering relevant properties of the local interstellar medium and defining a sample interstellar mission, this paper considers possible interstellar applications of the electrodynamic tether, or EDT. These include use of the EDT to provide on-board power and affect trajectory modifications and direct application of the EDT to starship acceleration. It is demonstrated that comparatively modest EDTs can provide substantial quantities of on-board power, if combined with a large-area electron-collection device such as the Cassenti toroidal-field ramscoop. More substantial tethers can be used to accomplish large-radius thrustless turns. Direct application of the EDT to starship acceleration is apparently infeasible.

Keywords: interstellar travel, tethers, world ships, ramscoops, thrustless turning, on-board power sources

1. Introduction:

The Electrodynamic Tether, or EDT, is conceptually one of the simplest in-space propulsion concepts. The tether consists of a long, conducting strand. Electrons are collected from the ambient plasma at one end, flow along the tether, and are emitted at the other end of the tether. In certain cases, the tether itself collects electrons from the local plasma, and a dedicated electron-collection device is not required. The fundamental physics and engineering of EDT power generation was demonstrated in space by NASA's Tethered Satellite System in 1996 [1].

In this paper, we consider three possible applications of the EDT to interstellar travel. First, we consider the feasibility of using an EDT to supply on-board power to a starship, at the expense of ship kinetic energy relative to the interstellar magnetic field. Then, we examine the utility of the EDT to perform thrustless turning or course correction. Finally, we examine whether the interaction of the tether and the interstellar magnetic field can be applied to efficiently propel a starship without the expulsion of reaction mass.

Before considering these potential applications, it is necessary to discuss properties of the local interstellar medium. Also, the design parameters for a reference starship must be considered.

1.1 The Local Interstellar Medium:

Our solar system is located in a low-density, high-temperature portion of the interstellar medium, which has been dubbed the "local bubble" and is typical of the intercloud medium. Pikel'Ner has estimated the interstellar magnetic field strength (B_{ism}) as 5×10^{-10} weber/m^2[2]. More recently, Valle has determined the interstellar magnetic field strength to be the order of a few 10^{-10} weber/m^2 [3].

Redfield and Linsky estimate the local interstellar medium moves at 25.7 km/sec relative to the Sun [4]. This velocity seems typical of most interstellar clouds.

According to Spitzer and Jenkins [5], the temperature of the local interstellar medium (T_{lism}) is 6,000 - 10,000 K; the local interstellar neutral-hydrogen density ($n_{H,neut}$) is approximately 0.1 cm^{-3}; and the local interstellar-electron density (n_e) is 0.02 - 0.03 cm^{-3}. More recently, Puyoo and Ben Jaffel [6] have extrapolated Voyager UV Lyman-α data to determine that $n_{H,neut}$ is approximately 0.24 cm^{-3} and $n_e / (n_e + n_{H,neut})$ is approximately 0.14.

Mathis tabulates properties of the warm intercloud material in the solar vicinity [7]. The hydrogen density is around 0.1 cm^{-3}, the electron density is approximately 0.025 cm^{-3}, and the temperature is approximately 8,000 K.

It is assumed in these calculations that the motion of interstellar magnetic field lines is identical to the velocity of the local interstellar medium. If these field lines are fast moving, perhaps due to a local, undiscovered magnetar -- a highly-magnetic, rapidly rotating neutron star -- there will be other applications of the EDT, as has been discussed in previous publications [8,9].

Based upon the preceding discussion, we adopt the following values for various parameters of the local interstellar medium:

$B_{ism} = 5 \times 10^{-10}$ weber/m^2
$T_{lism} = 6{,}000$ K
$n_e = 3 \times 10^4$ m^{-3}

1.2 The Reference Starship:

We assume a flotilla of interstellar arks that might rendezvous in interstellar space to construct a worldship. The payload mass of each ship is 5×10^6 kg. Each ship can support a population of 50 [10]. The interstellar cruise velocity of the starships is 0.003c

(900 km/sec). At this velocity, the ships require about 1,433 years to reach Alpha Centauri.

Although nuclear-pulse-propelled world ships are certainly an option [11], it is assumed here that the primary propulsion for these ships is the ultra-thin, space-manufactured solar sail unfurled as close to the Sun as possible at the perihelion of a parabolic or hyperbolic solar orbit [12]. After acceleration to interstellar cruise velocity, it is also assumed that sail and cables are wound around the habitat section to provide extra cosmic ray shielding. The sail is unfurled again for deceleration at the destination star.

Table 1 presents two possible approaches to this mission, and the starship parameters considered in this paper. In all configurations, diamond-strength cables are assumed. Configuration 1 is an aluminum-boron bi-layer sail, which is partially unfurled at 0.01 AU from the Sun [13]. Configuration 2 is a perforated aluminum sail partially unfurled at 0.044 AU from the Sun [14]. Both pre-perihelion solar orbits are parabolic. Since the baseline sailcraft for this analysis is somewhat faster, either more advanced sail/cable materials are required or the pre-perihelion orbit is hyperbolic.

2. Application of an Electrodynamic Tether to Obtain On-Board Power:

During its 1,400-year cruise to α Centauri, the habitat population will require a power source to ensure their survival far from a star. Bock et al has estimated the average on-board power requirement for a space habitat is 12 kilowatts per person [15]. For a population of 50, the required average on-board power is 0.6 megawatts.

A nuclear reactor is one option for on-board power, but Mauldin questions the reliability of such a reactor during a millennial journey [16]. One possible back-up power source is to use an EDT to obtain electrical power from the interstellar magnetic field at the expense of a small decrease in interstellar cruise velocity.

Figure 1 presents an illustration of an EDT tether utilized to obtain energy from the interstellar magnetic field. An electron scoop, possibly modeled upon Cassenti's toroidal-field ramscoop [17], collects interstellar ions and protons at the uppermost habitat section. Protons are emitted as shown, and the electrons are directed through the tether of length L. The electrons are then emitted from the tether at the lower habitat section. The reason for dividing the habitat is to reduce tether torquing.

According to the elementary physics of motional electromagnetic force [18], the EMF (ε) on a tether of length L moving at a velocity V_{ship} perpendicular to the interstellar magnetic field (B_{ism}) is:

$$\varepsilon = V_{ship} B_{ism} L \text{ volts.} \tag{1}$$

Since electrical power (P) is the product of EMF and current (i),

$$P = V_{ship} B_{ism} L\, i \text{ watts.} \tag{2}$$

As discussed above, the ship's velocity is approximately 900 km/sec, and the strength of the interstellar magnetic field is 5 X 10^{-10} weber/m^2. If we assume a tether length of 1,000 km, substitution in Eq. (1) reveals that ε = 450 volts. Since 0.6 megawatts of electrical power are required, Eq. (2) reveals that the tether current (i) is 1,333 amps.

Tether minimum mass (M_{teth}) and dimension can be calculated by assuming a superconducting tether. Using a projected superconductor current/density mass ratio of 5 X 10^6 amp-m/kg [8],

$$M_{teth} = i\, L \,/\, (5 \text{ X } 10^6) \text{ kg.} \tag{3}$$

Substituting i = 1,333 amps and L = 1,000 km, tether mass is estimated to be 270 kg. Assuming a tether-material specific gravity of 3 and a circular tether cross-section, the tether thickness is approximately 0.35 mm. Since the tether mass is so low, one option is to increase tether length and reduce the supercurrent.

2.1. Electron-Collector Radius:

To find the effective field radius of the electron collector (R_{sc}), first note that the quantity of electrons collected per second is;

$$Q_{elec} = n_e V_{ship} \pi R_{sc}^2 \quad \text{electrons/second.} \tag{4}$$

Since the electron's charge q is 1.6 X 10^{-19} coulombs, the current supplied to the tether is:

$$i = n_e V_{ship} \pi R_{sc}^2 q \quad \text{amps.} \tag{5}$$

Since the tether current is 1,333 amps, n_e = 3 X 10^4 m^{-3} and the ship's velocity is 900 km/sec, the effective electron-collector radius is approximately 313 km.

A physical structure of this size would be massive indeed. However, since Cassenti's toroidal-field ramscoop consists of a tenuous array of superconducting wires [17], the mass of the electron collector will be of the order 10^5 kg.

2.2. Electron Collection Using a Bare Electrodynamic Tether:

Under certain conditions, it is possible to dispense with the electron collector. As discussed by Gilchrist et al [19], a bare (unsheathed) EDT in a non-flowing plasma can collect electrons directly from that plasma.

For the case of high potentials ($\varepsilon >> k\, T_{lism}/q$, where k is Boltzmann's constant = 1.381 X 10^{-23} J K^{-1}), the current collected by the bare tether is expressed:

$$i_{coll} = 0.45\, n_e A_p\, q\ [\,(q\, \varepsilon)\ /\ (m_e)]^{0.5} \text{ amps,} \tag{6}$$

where A_p is the tether area (length x thickness) and m_e is the electron mass (9.1 X 10^{-31} kg).

Since A_p = 350 m^2 for the tether under consideration, substitution in Eq. (6) yields a collected current of 6.7 X 10^{-6} amps. Direct tether electron collection, therefore, seems impractical for this interstellar application.

But the validity of this approximation can be challenged on two fronts. First of all, Eq. (6) applies only for the high voltage case when $\varepsilon >> k\, T_{lism}/q$. Substitution reveals that this is indeed the case.

More significantly, Eq. (6) is accurate for the case of non-flowing plasma, where random electron thermal motions are at least of the same order of magnitude as the plasma flow rate, which in this case is 900 km/sec.

The random electron thermal velocity (V_{rtv}) can be calculated using the equation [20]:

$$1/2\ m_e\ V_{rtv}^2 = 3/2\ k\ T_{lism}\ \text{Joules} \quad (7)$$

Substitution in Eq. (7) reveals that the random electron thermal velocity is approximately 523 km/sec, certainly of the same order of magnitude as the plasma flow rate past the tether. It is therefore safe to conclude that an electron-collection device is necessary in the low-electron-density local interstellar medium.

2.3. Tether Drag Effects:

Two contributors to drag on the EDT will be tether collisions with neutral hydrogen atoms and interstellar dust grains. To evaluate neutral-atom drag, first recall that neutral-hydrogen density in the local interstellar medium (n_h) is approximately 10^5 atoms/m^3. The hydrogen mass per second striking the tether is:

$$dM_h/dt = n_h\ m_h\ V_{ship}\ L\ T_{teth}\ \ \text{kg/sec}, \quad (8)$$

where m_h is the hydrogen atom mass (1.67×10^{-27} kg) and T_{teth} is the tether thickness (3.5×10^{-4} m). Substituting in Eq. (8), $dM_h/dt = 5.3 \times 10^{-14}$ kg/sec. Assuming fully elastic tether-hydrogen collisions, the deceleration of the starship due to tether-hydrogen collisions is $2\ (dM_h/dt)\ V_{ship}\ /\ M_{ship}$ m/sec^2, where M_{ship} is the ship mass. Therefore, ship deceleration due to these collisions is an inconsequential 3×10^{-15} m/sec^2. During a 1,400-year voyage at an initial velocity of 900 km/sec, these collisions reduce spacecraft velocity by approximately 10^{-4} m/sec.

To prevent tether erosion by impacting interstellar dust grains, a dust screen could be placed in front of the tether to break dust particles down to atomic size. The dust density in the local interstellar medium is approximately 10^{-6} dust grains /m^{3,} and each grain has an approximate mass of 10^{-17} kg [8]. Starship deceleration caused by tether-dust collisions is about an order of magnitude less than deceleration caused by collisions between the tether and interstellar hydrogen atoms.

2.4. Magnetic Braking:

Some deceleration of the starship will occur as it taps the interstellar magnetic field for on-board power. The product of the on-board power P derived from the interstellar medium in any time interval and that time interval will be equal to the starship's change in kinetic energy relative to the interstellar medium in that same time interval. Since the deceleration in any time interval is much smaller than the ship's interstellar cruise velocity (V_{ship}), the ship's magnetic-drag deceleration can be expressed:

$$dV_{ship}\ /\ dt = P/(M_{ship}\ V_{ship}), \quad (9)$$

Since $P = 6 \times 10^5$ watts, $M_{ship} = 3 \times 10^7$ kg, and $V_{ship} = 900$ km/sec, the magnetic drag deceleration of the starship is approximately 2×10^{-8} m/sec^2.

During a 1,400-year voyage, magnetic braking will decrease the starship's interstellar cruise velocity by about 1 km/sec. This is a velocity decrease of approximately 0.1 percent, which increases the voyage duration by less than two years.

3. Magnetic Thrustless Turning and the EDT:

As described by Norem and Forward, one way of modifying the trajectory of an interstellar spacecraft without propellant expulsion is Lorentz-force turning in the interstellar magnetic field [20, 21]. This trajectory alteration is affected by the interaction between the interstellar magnetic field and an electrostatic charge or magnetic field on the starship.

Assuming the ship's magnetic field is produced by the uni-directional current in a tether and the tether current is approximately perpendicular to the interstellar magnetic field, the radius of the thrustless turn (R_{tt}) can be estimated using Eq. (7.10) of Ref. 7:

$$R_{tt} = M_{ship} V_{ship}^2 / (i \, L \, B_{ism}) \text{ meters.} \tag{10}$$

Substitution in Eq. (10) reveals that the radius of the thrustless turn in the local interstellar medium for the tether, starship mass and starship velocity considered here, is approximately 3.7×10^{16} km.

When the starship has traveled for about 2.3×10^{17} km, its trajectory has been altered by 360 degrees. But at 900 km/sec, the starship under consideration travels approximately 2.8×10^{10} km per year. Thus, the trajectory direction is altered by about 4-$\times 10^{-5}$ degrees per year. During a 1,400-year journey, the trajectory bend angle is approximately 0.06 degrees.

To obtain a six-degree trajectory modification during a 1,400-year journey with the tether current assumed, the tether length must be increased by a factor of 100X to equal 10^5 km. This would increase tether mass to 2.7×10^5 kg.

4. Direct Starship Propulsion by Tether/Interstellar-Magnetic-Field Interaction:

Referring to the above discussion and Fig.1, a potential of 450 volts and an on-board power of 6×10^5 watts can be derived by the interaction of the interstellar magnetic field and the tether supercurrent, at the expense of starship kinetic energy. If an on-board power system, such as a nuclear reactor, is used to supply power to the interstellar medium, by driving the supercurrent in the direction opposite to that shown in Fig. 1, the starship's kinetic energy will increase.

Applying Eq. (9) to the 3×10^7 kg starship moving at 900 km/sec, the acceleration is approximately 2.2×10^{-8} m/sec^2. In one year, the starship's velocity increases by 0.7 m/sec. If the reactor is continuously operated during a 1,400-year journey, the starship's velocity will increase by 1 km/sec.

Direct starship propulsion by tether interaction with the local interstellar magnetic field is not an effective drive mechanism. A much more effective application of an on-board nuclear reactor for course correction and small velocity alterations would be nuclear-electric propulsion, or NEP.

5. Conclusions:

Electrodynamic tethers have a number of applications to interstellar travel. Consideration of a model for a sample world-ship mission through the local interstellar medium reveals that the interaction between an EDT and the interstellar magnetic field can satisfy on-board starship power requirements without an inordinate amount of starship deceleration.

Thrustless turning using an EDT's interaction with the interstellar magnetic field will allow for course correction and rendezvous of solar sail-launched modules in interstellar space. It will not, however, allow rapid thrustless circling to allow a starship to re-enter a power beam or make numerous solar passes [20-22].

Direct starship propulsion by the interaction of an EDT and the local interstellar magnetic field appears to be ineffective.

The work discussed here in no way exhausts possible EDT applications to interstellar travel. For instance, one might consider "fuel-less turning."

As well as collecting electrons, Cassenti's toroidal scoop could be utilized to collect positive ions. These could be directed into an ion accelerator, powered by the EDT and emitted at a selected angle to the starship's trajectory. Trajectory direction could thereby be altered without the expulsion of on-board propellant, at the cost of a slight reduction in starship velocity.

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TABLE 1. *Two Sailcraft Configurations from the Literature and the Baseline Spacecraft for this Study. Each Sail is 1/4 Unfurled at Perihelion. The Shield Factor is (Payload + Cable + Sail Mass) / Payload Mass.*

Configuration 1: Aluminum/Boron Sail, Payload Mass= 5 X 10^6 kg [13]
Sail Areal Mass Thickness = 6 X 10^{-5} kg/m^2 Reflectivity = 0.9, Emissivity = 0.5, Perihelion = 0.01 AU Sail Radius = 300 km, Peak Acceleration = 2 g Shield Factor = 6.5, Time to α Centauri = 1520 years
Configuration 2: Perforated Aluminum Sail, Payload Mass= 5 X 10^6 kg [14]
Sail Areal Mass Thickness = 1.62 X 10^{-5} kg/m^2 Reflectivity = 0.43, Absorbtivity = 0.10, Emissivity = 0.38, Perihelion = 0.044 AU Sail Radius = 800 km, Peak Acceleration = 0.94 g Shield Factor = 9.68, Time to α Centauri = 1605 years
Baseline Spacecraft for This Analysis
Payload Mass = 5 X 10^6 kg Total Spacecraft Mass = 3 X 10^7 kg Time to α Centauri = 1433 years Interstellar Cruise Velocity = 0.003c

Fig.1. Application of an EDT to Obtain On-Board Power for a Starship. The Interstellar Magnetic Field is Directed into the Page.