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DRAG AND PROPULSION OF LARGE SATELLITES IN THE IONOSPHERE; AN ALFVÉN PROPULSION ENGINE IN SPACE

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A conductor moving across a magnetic field $\vec{B}_0$ in a vacuum will have an induced charge separation sufficient to cancel the electric field $\vec{E}=\vec{v}_c\times\vec{B}_0/c$ seen by a co-moving observer. When the surrounding medium is a plasma, there exist possible mechanisms for charge to be conducted away with a resulting dc current flowing through the conductor. The circulation of charge by means of the generation of Alfvén waves provides such a mechanism whenever some action, such as photoemission, is present to overcome the electronic work function of the conductor. It is particularly effective for very large conductors moving in or above the earth's ionosphere. When applied to a study of the Echo satellite it gives rise to a significant damping of the orbit as mechanical energy is converted to that of Alfvén radiation. The calculated drag is equal to that observed for the orbit of Echo I and attributed in earlier studies to the mechanical drag of a considerable nonionized atmospheric density. In an appropriately designed satellite the drag force can be altered by variations of an internal resistance or the associated dc current flow can be tapped as a battery. With a source of electrical power to reverse the current flow the drag force can be converted to a propulsion mechanism: The satellite pushes on the earth's magnetic field without any emission of propellant.

We exploit the analogy, valid at frequencies much less than the ion cyclotron frequency Ω_i, between a collisionless plasma in a magnetic field and a series of transmission lines (parallel to the magnetic field) imbedded in a medium of high dielectric constant. The moving conductor with its induced charge separation is, in a sense, in successive contact with different transmission lines as it moves. In the collisionless plasma with infinite conductivity along $\vec{B}_0$, but with zero conductivity perpendicular to $\vec{B}_0$, it induces an impulse (Alfvén wave) traveling one-dimensionally along the magnetic field which carries a charge separation and effectively completes the circuit in which the moving conductor is a dc battery. (For the moment we ignore any effects of a finite conductor work function.) These Alfvén waves accompanying the conductor form current wings, as shown in Fig. 1. The wings carry the charge separation required to maintain field $\vec{E}$ perpendicular to $\vec{B}_0$ and independent of distance along the wing. The field $\vec{E}$ equals that at the conductor; i.e.,

$$\vec{E}=\vec{v}_c\times\vec{B}_0/c, \qquad (1)$$

tangential to the conductor surface and between the top and bottom wings. The wing makes an angle α with the field lines such that $\tan\alpha=v_c/v_a$, where v_c = speed of the conductor and v_a

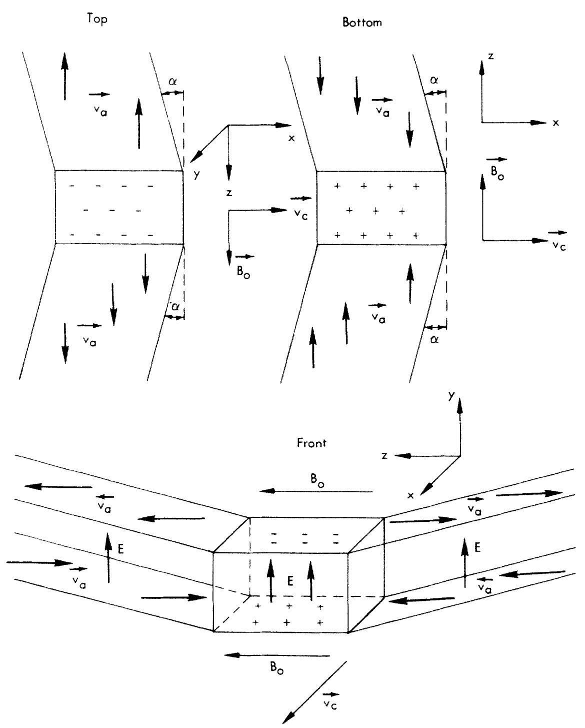

FIG. 1. Alfvén wings generated by an ideal conductor in a collisionless plasma.

≡ Alfvén speed. In the small-amplitude low-frequency approximation, valid when $v_c \ll v_a$, the wings extend until damped by electron collisions.

Our considerations of the Alfvén disturbance apply only to low-frequency waves with $\omega < \Omega_i \sim 500$ to 2000 cps for ~1000-km and ~200 cps for ~200-km altitude earth orbits. For this reason we limit our study to large conductors, since the typical frequency radiated by a moving source of dimension L and velocity v_c is

$$\omega \sim v_c/L, \tag{2}$$

and for $v_c \sim 7\times10^5$ cm/sec for a satellite in earth orbit and $\omega < 1000$ cps, $L > 10$ meters. The dielectric tensor of the magnetized plasma is given in the low-frequency limit by

$$\epsilon_{\parallel} = \epsilon_{zz} \cong 1 + \frac{4\pi\sigma_0}{i\omega}\frac{1}{(1+i\omega\tau_e)},$$

$$\epsilon_{\perp} = \epsilon_{xx} = \epsilon_{yy} \cong 1 + \frac{4\pi\sigma_0}{i\omega}\left(\frac{1+i\omega\tau_i}{\Omega_e\tau_e\Omega_i\tau_i}\right), \tag{3}$$

with all other components vanishing to leading order. $\sigma_0 \equiv n_e e^2\tau_e/m$ is the specific electrical conductivity of the plasma, and $n_e \equiv n$ is the electron (ion) number density in the neutral plasma. Electron and ion collision frequencies, $\nu_e = 1/\tau_e$ and $\nu_i = 1/\tau_i$, vary strongly in the ionosphere as functions of altitude[1] and must be included in a detailed study since they may be comparable with ω. Relative to the gyrofrequencies, however, they are negligible and are neglected throughout.

In the limit of a lossless, i.e., collision-free, plasma,

$$\epsilon_{\perp} \cong 1 + c^2/v_a^2,$$

$$\epsilon_{\parallel} \cong 1 - \omega_p^2/\omega^2, \tag{4}$$

where $\omega_p \equiv (4\pi ne^2/m)^{1/2}$ is the plasma frequency, and $v_a \equiv (B_0^2/4\pi\rho_i)^{1/2}$ defines the Alfvén velocity in terms of the magnetic field strength B_0 and the ionic mass density $\rho_i \equiv nM_i$. Numerically, the plasma frequency varies from $\omega_p \sim 6\times10^7$ cps at altitudes of 300 km corresponding to electron densities up to 10^6/cm^3, to $\omega_p \sim 4\times10^6$ cps at altitudes of 1600 km and electron densities of $\sim5\times10^3$/cm^3. The Alfvén velocities rise from values $v_a \sim 2\times10^7$ cm/sec at the 300-km altitude to $v_a \sim 10^9$ cm/sec at the 1600-km altitude. The ratio of parallel to transverse components of ϵ is very large; for the parameters of interest to us, $|\epsilon_\parallel/\epsilon_\perp| > 10^3$. This large ratio admits an Alfvén wave which propagates in the direction parallel to $\vec{B}_0$ only. Essentially, the electrons and ions find themselves wrapped around the magnetic field lines, but free to move along the $\vec{B}_0$ direction.

We have solved the Maxwell equations with the dielectric tensor (3) for the lossless medium with a current and charge source provided by the moving conductor shown in Fig. 1. The current in the moving conductor flows mainly in the y direction to maintain the charge separation. Since $v_a \gg v_c$, the wavelength of the disturbance along the $\vec{B}_0$ direction is much larger than the conductor dimensions

$$\lambda_{\parallel} = v_a/\omega \approx (v_a/v_c)L \gg L, \tag{5}$$

whose detailed geometry is not significant. Our formal solution is valid to first order in the Alfvén field strengths and confirms the general features discussed so far. There is a tangential electric field directed between the upper and lower wings of the Alfvén disturbance. It is continuous across the conductor surface and is fixed by the motional electric field in the conductor according to (1). A constant potential V is maintained between the wings a distance M apart with

$$V = -EM = (v_c/c)B_0M. \tag{6}$$

The magnetic field of the Alfvén wave is determined by $\partial\vec{h}/\partial t = \mathrm{curl}\,\vec{E}$ and Eqs. (2) and (5). Between the wings it is transverse in the x direction, and of magnitude

$$h = \frac{v_c}{v_a}B_0 \approx 4\times10^{-2}B_0 \text{ at 200-km altitude,}$$
$$\approx 10^{-3}B_0 \text{ at 1600-km altitude,} \tag{7}$$

plus correction terms near the edges from the fringing fields. A small ratio $(h/B_0) < 1$ is a necessary criterion for the linear approximation we have made.[2]

From the strength of the magnetic field (7), the power radiated in the Alfvén disturbance is computed to be

$$P = \frac{1}{4\pi}h^2 2(ML)v_a = \frac{B_0^{\ 2}}{2\pi}\frac{v_c^{\ 2}}{v_a}(ML), \tag{8}$$

where $2MLv_a$ is the volume filled per second by an energy density $h^2/4\pi$; the factor of 2 takes into account the existence of wings extending in both directions along $\vec{B}_0$. From Eq. (8) and Eq. (6) for the potential difference between the top and bottom wing, the current flow in the conductor is

$$I = \frac{P}{V} = \left(\frac{cv_c}{v_a}\right)\left(\frac{B_0}{2\pi}\right)L. \tag{9}$$

The effective impedance of the plasma for this current flow is then defined as

$$Z = V/I = 2\pi(v_a/c^2)(M/L). \tag{10}$$

In terms of these familiar quantities of electrical circuit theory the Alfvén wings may be interpreted as one-dimensional open-ended transmission lines of impedance Z across which a potential V is applied. In this ideal limit of a lossless medium there is an infinite resistance between the upper and lower lines (or Alfvén wings) and zero resistance along them. Finally, from Gauss's law, the surface charge density in the wing is

$$\Sigma_{\mathrm{ch}} = \frac{D}{4\pi} = \frac{1}{4\pi}\frac{c^2}{v_a^{\ 2}}\frac{v_c}{c}B_0 = \left(\frac{cv_c}{v_a^{\ 2}}\right)\frac{B_0}{4\pi} \text{ esu/cm.} \tag{11}$$

The large surface charge density arises from the enormous dielectric constant $\epsilon_\perp$, with values between 10^3 and 10^6.

We turn next to the three important practical factors modifying our considerations when applied to a real conductor such as Echo I moving through a real plasma such as the ionosphere at 1600-km altitude. These are effects of (1) collisions in the plasma, (2) a finite work function and space charge limiting the electron current flow out through the surface of the conductor, and (3) finite internal resistance in the conductor. We have studied these in detail[3] and comment here briefly only on our conclusions. The primary effect of collisions in this case is to lead to appreciable spreading of the Alfvén wings and to limit severely the frequency range in which the simple one-dimensionally propagating Alfvén solution applies. Only the modes with $\omega < 100$ cps can be described accurately by our solution, but according to Eq. (2) the frequency spectrum from the Echo-I satellite of typical dimension $L \sim 30$ extends up to ~ 250 cps. Since the power spectrum (i.e., the square of the Fourier integral of the spatial form) is approximately flat, the calculated drag is reduced by $\sim(10/25)^2 \sim \frac{1}{6}$ from the values computed from Eq. (9). The subsequent spreading is such as to increase the lateral dimension of the Alfvén wings by a factor ~ 10 at a distance of 3000 km from the satellite. Photoelectric emission in the daytime due to the incident flux of solar photons was found to be necessary and sufficient to overcome the work function at the Echo surface and to supply the electrons for the currents that maintain the fields in our solution; space-charge effects are insignificant. Finally, the internal resistance of the Echo conducting surface (a few microns of aluminum evaporated onto a Mylar base) is negligible compared with the effective plasma impedance (10), and there is no appreciable diminution of power or current flow.

The significance of these results for the Echo-I orbit is as follows: After other effects[4] such as solar pressure and electrostatic charging have been taken into account, atmospheric drag causing a power dissipation of $\sim\frac{1}{3}$ watt at a 1600-km altitude has been invoked to account for the observed orbit. This latter factor plays a significant role even at tiny densities above 1000 km because of the very abnormally large ratio of surface area to mass of Echo I ($\pi R^2 \simeq 6\times 10^6$ cm^2; weight ≈ 150 lbs). In fact, the detailed analysis of Echo's orbit has yielded a "measurement" of the mass density in the upper ionosphere. To account for the observed drag the needed mass density[4] is given as $\rho_{\text{mass}} = 1.2\times 10^{-18}$ g/cm^3 at this altitude. However, back-scatter radar measurements have found[5] $\sim 5\times 10^3$ electrons/cm^3 at 1600 km, and the corresponding ion mass density is $\approx 3\times 10^{-20}$ g/cm^3 for a molecular mass of $4M_p$ (for He^+) and $\approx 10^{-20}$ g/cm^3 if the ions are H^+. Thus there can be, at most, a few percent ionization at these altitudes if a mechanical drag of $\frac{1}{3}$ watt is necessary.

The magnetohydrodynamic braking of Echo I from radiation into the Alfvén mode is $P\sim\frac{1}{4}$ watt, very close to the required damping, as computed from Eq. (8) with the spatial frequency reduction factor of $\frac{1}{8}$ discussed above, together with another factor of $\frac{1}{2}$ for the fraction of time that Echo I is in the daytime sky, since only then does the sun's radiation maintain the photoelectric current. The new drag mechanism described here is of the right order of magnitude to explain the observed orbit parameters of Echo I without the requirement of a high value of the ionospheric mass density relative to ion density.

Direct experimental confirmation of the ideas presented here is clearly highly desirable —particularly in view of the very qualitative nature of our results as applied to Echo I which is somewhat too small to meet fully the criteria for the Alfvén regime of parameters. This confirmation could be achieved by observation of the Alfvén wings by specular reflection of radar from the surface-charge layer computed from (11), which increases the electron density by ~15% above its ambient value for a wing thickness $\sim\frac{1}{2}M\sim 15$ meters. As remarked earlier, an ionospheric disturbance is predicted extending perhaps many hundreds or even thousands of kilometers along field lines from Echo I. This may explain why Echo-I transits were seen in instances when the radar cross section of the body itself was too small to be seen above the instrumental noise.[6] In these same measurements ionospheric disturbances of duration ±20 minutes before and after transit of Echo I above the radar sighting were often recorded and could be explained if the Alfvén wings extend as a detectable charge separation along a magnetic-field line for a distance of a few thousand kilometers.

For Echo I the power level generated in the Alfvén disturbance was of the order of a watt. It is evident that large conductors ($L\sim M\sim 100$ meters) at lower altitudes (~200-500 km with $v_a\sim 2\times 10^7$ cm/sec and $B_0\sim 0.4$ gauss) can dissipate power in the Alfvén mode at the level of kilowatts when crossing field lines. With these parameters we find from Eqs. (6), (9), (10), and (11) $P=8$ kilowatts, $V=30$ volts, $I=130$ amperes in each wing, and $Z=0.23$ ohm.

The high level of power generated by the Alfvén disturbance invites speculation on ways of making practical use of it. If used passively as a controllable drag mechanism it can serve (1) as a means of converting satellite kinetic energy to electrical power, (2) as a way of bringing satellites to lower altitudes without propellant, (3) to adjust satellite attitudes by exploiting torques. If used in conjunction with an on-board source of electrical power (viz., small nuclear reactors or solar panels) it can serve (4) to counteract atmospheric-drag effects on satellites and even propel them to higher altitudes, (5) as a means of storing energy by converting it temporarily to satellite kinetic energy, (6) to maneuver the position and attitude of a space craft (without propellant) by pushing on the earth's magnetic field. For these uses one envisages flying a rigid "kite" consisting of two 100-meter-long conducting slabs each ~5-10 meter across, connected by a conducting rod of 100-meter length, oriented perpendicular to $\vec{B}_0$, through which the current flows. For passive use, a low-impedance motor (~0.23 ohm) will deliver a power $\sim\frac{1}{4}\times 8$ kilowatts when inserted in series into the 100-meter connecting rod. By adjusting or short circuiting the lever arms of the kite, the drag can be reduced or eliminated, or torques about $\vec{B}_0$ generated.

If a source of electrical power is available on the satellite, the direction of the drag currents can be reversed and the drag converted to a push without the emission of propellant. The advantage of an Alfvén propulsion engine over propulsion by a small rocket engine lies in those circumstances in which the power originates from solar panels or a nuclear generator as opposed to the consumption of a heavy fuel which could just as well be used as a propellant.

Among the problems facing a large manned orbiting laboratory (MOL) is atmospheric drag, a major source of orbit degradation. For a 20 000-lb MOL with a 7-m^2 cross section at a 100-mile altitude, it is estimated that the drag would dissipate power at a 7-kilowatt rate, lowering the orbit ~15 km/day. To compensate this drag we propose flying the "kite," but with a power source aboard MOL to drive the current backward, thereby gaining the 5-10 kilowatt of power required to neutralize the drag loss and to maintain the altitude of MOL with a small increase of total weight in orbit; higher power levels could also be utilized to make MOL sail to higher altitudes (possibly for the purpose of storing electrical energy).

We may speculate on this kind of mechanism as a propulsion engine for flight to further reaches of space. For interplanetary travel typical parameters are $\vec{B}_0 \sim 10^{-5}$ gauss and densities ~10^{-23} g/cm^3, leading to Alfvén speeds of $v_a = 10$ km/sec. We are in the Alfvén regime if $\omega < \Omega_i \sim 10^{-1}$ cps, corresponding to a "kite" dimension of $L \sim 100$ km. With $v_c \sim v_a$, the maximum generated power is $P \sim \frac{1}{8}$ kilowatt.

The conversion of energy from gravitational attraction near another planet to electrical energy is also a possibility if both a reasonable magnetic field and ionospheric plasma are present.

Finally, note that the phenomenon discussed in this paper can be used to determine ionic mass densities in regions of known magnetic field strength, as both the Alfvén field strength and the power dissipation are proportional to $\rho_i^{1/2}$.

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[1]Satellite Environment Handbook, edited by Francis S. Johnson (Stanford University Press, Stanford, California, 1961).

[2]The change in direction of the charge flow away from the conductor due to $\vec{h}$ leads to a displacement no larger than the transverse dimension of the Alfvén wave at a distance of about one wavelength away from the conductor in the direction of $\vec{B}_0$. This is a rough sufficiency criterion for the neglect of higher order terms in computing current flows, power radiated, and drag on the satellite.

[3]A detailed account of this work has been submitted to J. Geophys. Res., and is presently available as a preprint from the Institute for Defense Analyses, 400 Army-Navy Drive, Arlington, Virginia.

[4]R. Jastrow and C. A. Pearse, J. Geophys. Res. 62, 413 (1957); I. I. Shapiro and H. M. Jones, Science 132, 1485 (1960).

[5]K. L. Bowles, Advances in Electronic and Electron Physics (Academic Press, Inc., New York, 1964), Vol. 19, p. 55; K. L. Bowles, G. R. Ochs, and J. L. Grenn, J. Res. Nat. Bur. Std. 66D, 395 (1962).

[6]M. Tiuri and J. D. Kraus, J. Geophys. Res. 68, 5371 (1963). We thank Dr. Allen M. Peterson for informative discussions on this point.

REMARK ON THE HYDROXYL ION SYSTEM IN ALKALI HALIDES*

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A recent contribution of Känzig, Hart, and Roberts[1] submitted to this journal reported on an experiment which measured the dielectric constant, ϵ, of OH^- in KCl. The striking observation was made that ϵ had a maximum at temperatures T_{max} which increased with concentration according to a law

$$T_{max} \simeq 0.05 N_d \,{}^\circ\mathrm{K},$$

where N_d = concentration of dipoles in units of 10^{18} cm^{-3}. The height of the maximum is rather insensitive to concentration varying between $\epsilon = 4$ and $\epsilon = 6$. Here ϵ refers to the OH^- system alone. The width of the peak varies more rapidly with N_d and is not inconsistent with a law proportional to N_d^2.

These data were interpreted by Känzig, Hart, and Roberts in terms of an ordered ferroelectric phase. It is the purpose of this Letter to point out the existence of a more likely interpretation in terms of a random antiferroelec-