Spacecraft Propulsion: New Methods

Abstract. *Cosmic plasmas contain energy which may be tapped and used for spacecraft propulsion. The energy needed for launching a spacecraft could be supplied to it from the ground through a plasma channel in the atmosphere.*

In a fascinating article entitled "The Relevance of Space," Arthur Kantrowitz (*1*) pointed out that the cost of the kinetic energy needed to put a 3000-kg spacecraft into orbit is less than $150 under the condition that the energy can be bought at the price a consumer of electricity on the ground is paying. This means that one of the reasons why space activity is so expensive is the extremely inefficient way energy is used for spacecraft propulsion. This is partially a result of the low exhaust velocity of the rocket gases, which implies that the total starting weight of the spacecraft must be two or three orders of magnitude larger than the payload.

An ingenious way of reducing the ejected mass is used in the electric propulsion devices developed by Ernst Stuhlinger (*2*) and others. By ejection of a plasma one can easily reach exhaust velocities of several tens of kilometers per second. The result is that the ejected mass may be of the same order of magnitude as the payload and the efficiency very high. The present limitation of this spacecraft propulsion device is that it draws its energy from solar panels, which, for mechanical reasons, cannot be made to deliver more than about 10 kw each. A nuclear reactor in the spacecraft may give much higher power, but it is a complicated and unpleasant device.

I shall discuss here some possible ways of furnishing a spacecraft with power to be used in a plasma propulsion motor.

Sailing in the solar wind. Because of its magnetization B, the solar wind, which moves radially outward from the sun with a velocity v, possesses an electric field E (seen from a fixed coordinate system):

$$\mathbf{E} = \frac{1}{c}\mathbf{v} \times \mathbf{B}$$

where c is the speed of light. With the normal values $B = 5 \times 10^{-5}$ gauss and $v = 4 \times 10^{7}$ cm/sec, we find (if v is perpendicular to B)

$$E = 2 \text{ volt/km}$$

a value which may increase by one order of magnitude (for example, in connection with solar flares). It may also be smaller for some periods. If a conducting cable with the length of, say, 500 km is placed in the direction of E, we could tap a voltage of 1000 volts under the condition that the transfer resistance between the ends of the conductor and the solar wind can be made small. If the cable consists of a number of wires of a superconducting material embedded in a thermal insulator, those wires that are not exposed to solar radiation may cool down by radiation so much that they become superconducting. A current of, say, 1000 amperes through the cable would give a power of 1 Mw. The project requires that three crucial problems be solved:

1) That a cable be manufactured with the required properties. In order to compete with other energy sources the power per mass must be at least of the order of 0.1 kw/kg (*2*), which means that the cable must not weigh more than 20 kg/km (*3*).

2) That the cable be deployed in space so that it becomes superconducting.

3) That electric contact be established between the solar wind and electrodes at both ends of the cable.

It seems reasonable that problems 1 and 2 can be solved. Concerning problem 3, a space-charge limited current is too small to be useful. However, if the electrodes are surrounded by a plasma, an arc discharge (or a corona discharge) may be produced. The plasma could be emitted from a gun near the electrode, or we may use the plasma which must be ejected in any case for the propulsion of the spacecraft.

It is not very obvious whether the electric contact with the solar wind will be a technically difficult problem or not. We know that the magnetosphere taps about 10^{12} watts from the solar wind (*4*). This is about two orders of magnitude greater than the solar wind kinetic energy passing a surface of the earth's cross section. (Hence, the electromagnetic tapping achieved by the magnetic field of the earth is much more efficient than a "mechanical" sail the size of the earth would be.) If in this project a power of 1 Mw is extracted, the result would just copy what nature does on a scale 10^{6} times larger.

Whenever the electric vector in the solar wind changes, the "sails" must be trimmed for the new wind situation.

In principle, the extraction of energy from the solar wind may give a spacecraft a velocity of the same order of magnitude as the solar wind. This would reduce travel times in space by two orders of magnitude.

Energy transfer à la Zeus. When Apollo 12 was launched, there were low clouds but no thunderstorm. When the spacecraft had disappeared in the clouds, lightning was observed in the region of sky where the spacecraft had last been seen. This effect was interpreted as due to the exhaust gases which facilitated a discharge of electrostatic charges in the clouds down to the ground. One cannot avoid thinking that it would be preferable to transfer power up to the spacecraft in this way.

In order to put a 3000-kg spacecraft into orbit, an energy of 10^{11} joules is needed. If an acceleration of $8g$ is allowed, an average power of 1 Gw is required during 100 seconds. We can easily tap a power of this order from an electric power network, but the difficulty is to transfer it to the spacecraft.

In a thunderbolt, a number of precursory discharges produce a conducting channel between a charged cloud at, say, a height of 5 km and the ground. When this has been achieved, the main discharge takes place. Often a series of discharges follows, showing that, once the channel is ionized, it has a considerable lifetime (up to 1 second). In a typical lightning we have a dissipation of 0.5×10^{9} joules (*5*), an energy comparable to what the acceleration itself requires in a fraction of a second.

If a spacecraft at launch is accelerated by two plasma guns at a large distance from each other, and electric arcs are produced between each of the plasma guns and the corresponding electrodes on the ground, it is possible that these arcs can be maintained during the launch through the atmosphere. The ground electrodes must have a voltage of several million volts, and the currents should perhaps be pulsed. If the arcs burn in the hot exhaust gases from the rocket, the power necessary to sustain them will be reduced, especially if the exhaust gases are seeded with easily ionized substances. The values given above for the power needed to make the paths of a lightning conducting seem not to exclude the possibility that an efficient energy transfer can be accomplished in this way.

If alternating current is used, it is

possible that only one transfer channel is needed. A thundercloud can store 10 to 50 coulombs. If the spacecraft is furnished with a number of sharp points, it could distribute electric charge through corona discharges to a vast region around it where charge can be stored. Also a transfer of wave energy along the conducting channel should be considered. The spacecraft must be accelerated up to a height of several hundred kilometers. When it has reached the ionosphere, the transfer problem takes on another aspect. The anisotropy of electric conduction in the earth's magnetic field could be used for energy transfer along the magnetic field lines. It is possible that the spacecraft trajectory should be made parallel to the magnetic field lines. The total power to be transmitted at the launch is comparable to the power of a very large magnetic storm. Our knowledge of the storm processes in the auroral zone will be valuable.

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References

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4. H. Alfvén and C. G. Fälthammer, *Cosmic Electrodyn.* 2, 78 (1971).
5. See, for example, M. A. Uman, *Lightning* (McGraw-Hill, New York, 1969).

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Intestinal Calcium Transport: The Role of Sodium

Abstract. *The role of sodium in intestinal calcium transport was investigated in everted rat intestine. Ethacrynic acid, but not ouabain, inhibited calcium transport. However, ouabain did inhibit net water transport and, therefore, sodium transport, establishing the dissociation of the two transport processes. In addition to a magnesium-dependent adenosine triphosphatase (activated by sodium and potassium), a phosphatase dependent on sodium and calcium was localized to the lateral and basal membrane fractions of the mucosal cell. Activity of the latter phosphatase, similar to calcium transport in intact tissue, was inhibited by ethacrynic acid and not by ouabain. Sodium, therefore, may participate in the calcium transport process by activating an enzyme complex, dependent on adenosine triphosphate, that mediates calcium transport.*

Although there is controversy about the mechanism of intestinal transport of calcium, the transport process is an energy-dependent, saturable process that moves calcium against concentration and electropotential gradients (*1*). Whereas the movement of calcium across the brush border of the intestinal epithelial cell does not require sodium, the expulsion of calcium from the cell at the basal and lateral membranes is presumably dependent on sodium (*2*, *3*). The nature of this dependency on sodium is not established. This relation between calcium and sodium in the intestinal cell is reminiscent of that in the renal tubule, where inhibition of proximal tubular reabsorption of sodium by saline infusion and volume expansion or by furosamide and ethacrynic acid is also associated with inhibition of calcium reabsorption (*4*). The similarities between renal and intestinal transport mechanisms (*5*) suggest that intestinal calcium transport might also be influenced by inhibitors of renal sodium transport.

Since ethacrynic acid and ouabain have been used to delineate two mechanisms of sodium extrusion from renal tubular cells, that is, sodium exchange and net sodium transport (*6*), these inhibitors may help to delineate the role of sodium in intestinal calcium transport. Accordingly, the influence of ethacrynic acid and ouabain on rat intestinal calcium transport was investigated. Ethacrynic acid inhibited net water and calcium flux across the intestine. Ouabain, however, inhibited water flux without concomitant inhibition of intestinal calcium transport. By fractionation of the mucosal cell, a phosphatase that is dependent on calcium and sodium was identified and localized to the plasma membrane at the base of the mucosal cell. This enzyme activity was also inhibited by ethacrynic acid but not by ouabain. The data suggest that this enzyme may mediate intestinal calcium transport and that sodium is required in the activation of this enzyme.

Calcium transport was studied with the use of everted 3.0-cm duodenal and ileal gut sacs prepared from Wistar rats (4 weeks old), by the method of Wilson and Wiseman (*7*). The animals were maintained on calcium-deficient diets for 5 days before they were killed. The incubation medium contained 140 mM NaCl, 0.4 mM $CaCl_2$, 2 mM glucose, and calcium-45 (0.02 μc/ml) in 4 mM phosphate buffer; final pH was 7.4. The everted sacs were filled with 0.15 ml of medium that contained the appropriate inhibitor of sodium transport. Ethacrynic acid (*8*) and ouabain (Sigma) were studied at concentrations from 0.1 to 1 mM. The intestinal sac preparations were incubated for 50 minutes at 37°C. Water is not actively transported by the intestine, and net water flux is totally dependent on net sodium transport (*9*). Accordingly, net water flux from the mucosal to the serosal side was used as an indicator of net sodium flux. Net water flux was determined gravimetrically as the gain in weight of the intestinal sac during incubation. The accumulation of calcium-45 in the fluid bathing the mucosal surface was also measured. Calcium transport was derived from the difference between the disintegrations per minute in the final sac content and this value in the initial sac content.

Ethacrynic acid inhibited calcium-45 transport and, to a lesser extent, net water flux in the everted duodenal and ileal sacs (Table 1). Ouabain inhibited net water flux in the ileum and, at higher concentrations (1 mM), it inhibited net water flux in the duodenum. Although the inhibition of water or sodium flux by ouabain was greater than that by ethacrynic acid, calcium transport was not inhibited by ouabain. Thus, under certain experimental conditions calcium transport may be independent of net water and sodium flux.

Calcium transport across the red cell membrane may be mediated by a calcium-activated, Mg-dependent adenosine triphosphatase localized in the red cell membrane (*10*). We proposed that a similar enzyme, dependent on calcium, exists in the mucosal cell membrane. Two additional constraints were imposed on the proposed enzyme complex: it would be activated by sodium and be localized on the serosal side of the mucosal cell. The movement of calcium across the luminal or brush border surface does not require sodium in the extracellular fluid (*1*) and is not the rate limiting, energy-dependent step in calcium uptake (*2*, *3*). Accordingly, we sought to identify an enzyme activity that is associated with the plasma membrane of lateral and basilar portions of