How, then, does the deafferented monkey with vision occluded obtain information about its own motor activities, as would be necessary, for example, when learning new movements? In this regard it is worth considering the possibility of the operation of central feedback mechanisms. Intracentral loops located appropriately could provide a means of monitoring central efferent activity before it has emerged into the periphery. Several pathways that could fulfill this function have been demonstrated to exist both anatomically and electrophysiologically, with points of inflection involving: afferent collaterals from the medullary pyramids to the dorsal column nuclei (*9*), laminae 4 to 6 of the dorsal horn (*10*), and the deep nuclei of the cerebellum (*11*). Other pathways of a similar nature probably exist elsewhere in the central nervous system. Descending activity could also be converted into a return pattern of signals by electrotonic or ephaptic conduction between descending and ascending fibers in adjacent tracts (*12*). A number of indications have made the dorsal spinocerebellar tract a subject of interest for current study in this regard. Another possibility is that no topographic feedback whatever, whether of central or peripheral origin, is necessary for the central nervous system to obtain information about movement-producing patterns of discharge. A set of neurons need only fire, and this event by itself would be sufficient to produce the encoding of that information. Feedback return would not be necessary to reiterate the data or to report on the consequences of the discharge. These different alternatives need not be viewed as mutually exclusive.

ROBERT COHN
ALFRED JAKNIUNAS, EDWARD TAUB
Institute for Behavioral Research, Silver Spring, Maryland 20910

References and Notes

1. F. W. Mott and C. S. Sherrington, *Proc. Roy. Soc. London* **57**, 481 (1895); C. S. Sherrington, *Brain* **54**, 1 (1931); A. M. Lassek, *J. Neuropathol. Exp. Neurol.* **12**, 83 (1953); T. E. Twitchell, *J. Neurophysiol.* **17**, 239 (1954).
2. H. D. Knapp, E. Taub, A. J. Berman, *Science* **128**, 842 (1958); *Exp. Neurol.* **7**, 305 (1963); E. Taub, G. Barro, B. Parker, T. Gorska, paper to be read at Neuroscience Society Meeting, Houston, October 1972.
3. E. Taub, R. Bacon, A. J. Berman, *J. Comp. Physiol. Psychol.* **58**, 275 (1965); E. Taub and A. J. Berman, *ibid.* **56**, 1012 (1963); E. Taub, S. J. Ellman, A. J. Berman, *Science* **151**, 593 (1966); E. Taub, D. Teodoru, S. J. Ellman, R. F. Bloom, A. J. Berman, *Psychon. Sci.* **4**, 323 (1966).
4. E. Taub and A. J. Berman, in *The Neuropsychology of Spatially Oriented Behavior*, S. J. Freedman, Ed. (Dorsey, Homewood, Ill., 1968), p. 173.
5. H. D. Knapp, E. Taub, A. J. Berman, *Exp. Neurol.* **7**, 305 (1963).
6. Confirmatory results have been obtained by other investigators: J. Bossom and A. K. Ommaya, *Brain* **91**, 161 (1968); D. Denny-Brown, *The Cerebral Control of Movement* (Liverpool Univ. Press, Liverpool, 1966), p. 54; S. Gilman, in *Modern Trends in Neurology*, D. Williams, Ed. (Butterworths, London, 1970), vol. 5, p. 60; D. Levine and A. K. Ommaya, *Arch. Neurol.*, in press; C. N. Liu and W. W. Chambers, *Acta Neurobiol. Exp.* **31**, 263 (1971); B. M. Stein and M. B. Carpenter, *Arch. Neurol.* **13**, 567 (1965); H. G. Vaughn, Jr., E. G. Gross, J. Bossom, *Exp. Neurol.* **26**, 253 (1970); C. J. Vierck, Jr., in *Somatosensory System*, H. H. Kornhuber, Ed. (Thieme, Stuttgart, in press).
7. Preliminary work along these lines has been carried out previously: in collaboration with T. Kokubu (1962), described in (*4*); J. Bossom and A. K. Ommaya, *Brain* **91**, 161 (1968); H. G. Vaughn, Jr., E. G. Gross, J. Bossom, *Exp. Neurol.* **26**, 253 (1970).
8. E. Taub, P. N. Perrella, G. Barro, *Trans. Amer. Neurol. Ass.*, in press.
9. For a partial summary see M. Levitt, M. Carreras, C. N. Liu, W. W. Chambers, *Arch. Ital. Biol.* **102**, 197 (1964).
10. For a summary see E. E. Fetz, *J. Neurophysiol.* **31**, 69 (1968).
11. For a summary see J. C. Eccles, M. Ito, J. Szentagothai, *The Cerebellum as a Neuronal Machine* (Springer-Verlag, New York, 1967).
12. W. M. Landau, *Science* **123**, 895 (1956).

5 September 1972

Electrodynamic Sailing: Beating into the Solar Wind

In a recent report Alfvén (*1*) suggests and comments upon a novel means of spacecraft propulsion based upon the extraction of energy from the electromagnetic field of the solar wind. He claims that it is conceptually possible to sail upwind by coupling the energy extracted to an appropriate engine, likely an ion engine. His emphasis upon energy is important, but both energy and momentum requirements must be met.

An electrically conducting spacecraft such as Alfvén proposes suffers from two energy loss mechanisms. One is associated with magnetohydrodynamic wave drag, and the other with internal ohmic losses in the unipolar circuit which the system comprises. To make propulsion feasible in the sailing sense of "beating into the wind," or even a "close reach," there are two requirements: (i) the spacecraft must be able to do work upon the solar wind in excess of the work done upon it by wave damping and ohmic losses; and (ii) the momentum exchange must favor the thruster (ion engine). It seems possible to achieve the second requirement since an engine ought to be able to partition momentum in the necessary way. However, it appears to be impossible to meet the first requirement, that is, to satisfy the principle of conservation of energy for sailing upwind.

Alfvén's suggestion that electric propulsion devices be used for attaining high exhaust velocity is basically the means whereby high momentum flux can be obtained while decreasing the fuel mass so that it is not necessary to accelerate as much dead weight of unburned fuel. This mass of unburned fuel which must be accelerated is really the cause of the inefficiency, and it explains why, in the theory of rocket propulsion, the specific impulse is a key parameter. This reasoning also explains why the high exhaust velocities attained in ion engines are so attractive. On the other hand, it has not been possible to design an ion engine capable of yielding the momentum flux required for escape from strong local gravitational fields such as that possessed by the earth, nor does such an accomplishment seem likely in the foreseeable future.

I would now like to turn in detail to Alfvén's scheme for "sailing in the solar wind." The electric field is given by

$$\mathbf{E} = (\mathbf{V} \times \mathbf{B})/c$$

where $\mathbf{V}$ is the velocity of the spacecraft seen from a frame co-moving with the solar wind bulk speed, $\mathbf{B}$ is the interplanetary magnetic field, and c is the speed of light. The production of 10^3 amperes in the example of Alfvén will produce a magnetohydrodynamic bow wave in front (on the upstream side) of his wire and result in wave drag from the production of waves which radiate away from the tips of the wire. Other geometries will produce similar results. The consequence is drag. In effect what takes place is a retardation of the spacecraft by distortion of the interplanetary field lines. This retardation can be viewed as a propulsion mechanism, but only in the sense that the spacecraft tends to come up to solar wind speed as the wind drags it along. Thus, in sailing terminology the spacecraft can only sail downwind (run before the wind) by this means.

In order that the spacecraft sail upwind magnetohydrodynamically the sense of current flow must be opposite to that derived from the electric field. In this case radiating Alfvén waves will be produced which tend to propel the spacecraft against the solar wind. Clearly these waves must still heel backward because of the supermagnetosonic speed of the solar wind with respect to the spacecraft, but the body forces they produce are opposite to the forces resulting from the wave field which the field $(\mathbf{V} \times \mathbf{B})/c$ would cause. In the subsonic case, for example, the plasma magnetic field would be warped so as to "slingshot" the spacecraft forward (*2*). In short, propulsive power cannot be derived from the electric field of the solar wind except in the sense of increasing the drag upon a spacecraft by the addition of magnetic forces to the plasma corpuscular bombardment already present. For sailing upstream the spacecraft must do work upon the solar wind; thus the ultimate source of the energy must arise from means other than the solar wind itself. For the case discussed here where propulsion takes place by means of hydromagnetic waves and for sailing upwind where the spacecraft does work upon the solar wind, the ultimate source of energy must come from some source other than the solar wind, that is, an internal battery.

Let us now turn to the case where an ion engine is used for propulsion; the energy is wholly derived from the motional electric field rather than from, say, a battery. In this instance the momentum exchange is brought about not only by means of hydromagnetic waves but also by means of the ion thrust. Waves result only in drag since the current sense is such as to produce a body force downstream. Alfvén's proposal calls for utilization of the kinetic energy of the solar wind to drive the ion engine so that sailing upwind can be achieved (presumably all points of the compass are now accessible). For this case it may be possible to remove the momentum restriction imposed upon magnetohydrodynamic propulsion, since a conceptual ion engine possibly might partition momentum in the way required for upstream motion (*3*). However, I think that serious objections remain with respect to the overall energy balance of the system. Since currents flow in response to the electric field (and are used to drive the ion engine), there will still exist electromagnetic body forces upon the spacecraft (including Alfvén's wire). This body force, **F**, varies with the current, the electric field, and the relative motion of the spacecraft and the solar wind. Therefore **F(V)** results in drag as in the earlier case, and consequently work is done by the solar wind upon the spacecraft at a rate given by

$$\dot{W}_{\mathrm{d}} = \mathbf{F}(\mathbf{V}) \cdot \mathbf{V} = \mathbf{V} \cdot (\mathbf{j} \times \mathbf{B})\, A \quad (1)$$

where **j** is the current density and A is the cross-sectional area of the wire. Furthermore,

$$\mathbf{j} = \sigma(\mathbf{V} \times \mathbf{B})$$

whereupon an expansion of the resultant vector triple product gives

$$\dot{W}_{\mathrm{d}} = -\sigma[(\mathbf{V} \cdot \mathbf{B}) - (|\mathbf{V}|\,|\mathbf{B}|)^2]A \quad (2)$$

(where σ is the bulk electrical conductivity) which attains a maximum value for **V** perpendicular to **B** for which case

$$\dot{W}_{\mathrm{d}} = \sigma E^2$$

At the same time the system constitutes a closed electric circuit endowed with an effective impedance Z due to all the individual impedances in series, including those in the solar wind which close the circuit. Thus an additional component of work done upon the spacecraft arises from ohmic dissipation given by

$$\dot{W}_{\mathrm{o}} = (jA)^2 Z$$

These losses are numerically equal to those associated with the drag, so that the total work done upon the spacecraft has the form $[2(jA)^2Z]$.

The available power from the solar wind is given by

$$\dot{W}_{\mathrm{m}} = jA\,|V|$$

so that

$$\dot{W} = 2(jA)^2 Z \quad (3)$$

The introduction of an engine is made in electrical series with the spacecraft or alternatively by drawing upon the heat generated in ohmic losses. One half of the work done upon the spacecraft appears as an increase in the downstream kinetic energy, whereas the other half is dissipated as heat. Energy can be extracted from the current flowing to drive an ion engine, but the maximum power available is determined by the power transfer theorem which restricts the available power to the amount lost in the remainder of the system. Since that amount is equal to $\dot{W}/2$, it seems clear that a net gain in forward kinetic energy can never be attained, since one half is irretrievably lost in wave drag and the other half is partitioned equally (at best) between ohmic losses and the energy needed to drive the engine. In this argument I ignore thermodynamic considerations which would be likely to increase the severity of the restrictions indicated here. Clearly then, even for a thermodynamically perfect engine, it would be impossible to return energy to the solar wind even in an amount equal to that which ends up as heat, which in turn is only half the total lost. Therefore, the energy balance requirement cannot be met.

It should also be noted that the hydromagnetic interaction can be classified as weak, intermediate, or strong. If the interaction is weak, the reaction of the induced field upon the solar wind is small so that the flow field of the solar wind about the spacecraft is not distorted. In this case a nearly undiminished value of **E** can be maintained. As the conductivity in the circuit is increased, say, by the introduction of superconductivity, the reaction becomes stronger, the flow field begins to separate, and the net **E** is decreased. The solar wind equipotentials tend to spread with the separation of the current flow, diminishing the drop across the spacecraft (*4*). Ultimately, as the currents grow stronger, the flow tends to separate completely and no further increase in current can be anticipated, no matter how large the conductivity is made (*5*). For a large object we would expect this condition to conform to the existence of a bow shock wave. For objects small as compared to the gyro radii of the ions and electrons, it cannot be said with confidence that a bow shock wave will form, but a saturation must still take place, because the saturation limit is imposed by the ultimate mechanical power in the solar wind coupled through the magnetic field. Even though the interaction region is permitted to grow, there must exist a limit upon its size, perhaps where the plasma adjusts itself to permit flow separation to take place.

The statements made above constitute an informal "proof" that it is impossible to satisfy the principle of the conservation of energy in the proposal of Alfvén. A conceptual laboratory demonstration adds a degree of heuristic conviction. Consider a pair of conducting rails shorted at one end with a movable armature, the rails threaded by a magnetic field. The arrangement constitutes a simple one-dimensional unipolar generator equivalent in principle to the spacecraft in the solar wind. The wind conforms to the rails and shorting section, and the spacecraft to the armature. Clearly a propulsive device drawing its power from the currents which flow cannot accelerate the armature. When the armature is standing, there is no current, and, if the armature is initially caused to move, it seems unlikely that the armature will be caused to accelerate by the motor which draws its energy from the motion itself.

But then how can a sailboat move against the wind? For high-performance yachts, sailing against the wind (close-hauled) is possible up to angles between the true wind vector and the boat direction of about 45°. The sail, being an aerodynamic section, provides lift normal to the wind direction; the lift can be resolved into a component in the forward direction which does work in moving the boat forward and a component to the leeward direction which does no work in the idealized case. The leeward component is corrected by keel "lift." (The boat maintains a keel angle of attack to provide this lift force.) In effect, the keel provides a force opposing part of the drag, thus removing the drag from energy considerations. If the spacecraft could be placed upon imponderable rails, then any drag component normal to the rails would be counterbalanced by the reaction of the rails, doing no work, and would thus be removed from the energy conservation equation; perhaps some points of the upwind compass could be attained by this means. However, the unrecoverable ohmic losses in the electrodynamic spacecraft have no parallel in the case for the boat, so that a detailed comparison seems unwarranted. A similar conclusion would apply to an iceboat; if the runners were removed so that it could slide in any direction without friction, then upwind sailing would be difficult at best and likely impossible. In spite of my arguments, I am reminded that bees were once shown theoretically to be incapable of flight, so perhaps some needed considerations are absent in my argument.

CHARLES P. SONETT
National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California 94035

References and Notes

1. H. Alfvén, *Science* **176**, 167 (1972).
2. S. D. Drell, H. M. Foley, M. A. Ruderman, *J. Geophys. Res.* **70**, 3131 (1965).
3. U. Fahleson, in preparation; personal communication.
4. I am indebted to J. Dungey for pointing this out in an earlier and different context.
5. C. P. Sonett and D. S. Colburn, *Phys. Earth Planet. Inter.* **1**, 326 (1968).
6. I thank my colleagues C. Harper, D. S. Colburn, and G. Schubert for criticisms.

26 April 1972; revised 16 June 1972

The first presentation (*1*) of the subject of sailing on the solar wind of necessity was quite short, and a more detailed treatment (*2*) is now in press. Considerable study and development may be necessary before the technical feasibility and economic advantage of solar wind sailing as compared to other methods of space propulsion can be evaluated. On the other hand, the fundamental principles and theoretical limitations of the method are fairly well understood since they follow from well-known laws of physics. Sonett raises several interesting questions, and, since they are mainly of a theoretical nature, they can be answered rather definitely.

The solar wind–powered vehicle (*1*) can be imagined in a number of different modifications (*2*). A common feature of all of these modifications is that a conducting path is established between regions of different electric potential and that the current flowing through this path is somehow utilized for propulsion. The conducting path may be a thin superconducting cable or a plasma jet or particle beam emitted from the vehicle.

The simplest type of vehicle could consist of a superconducting cable with suitable electrodes or emitters at its ends to facilitate electrical contact with the space plasma. The propulsive force is produced by the $\mathbf{I} \times \mathbf{B}$ interaction of the current in the cable and the solar wind magnetic field. As Sonett points out, the propulsive force will in this case always have a component in the downwind direction, that is, away from the sun. Clearly, a device of this kind will be most suitable for travel away from the sun. However, in many cases it will also be able to sail upwind quite efficiently in the combined force fields of the solar wind and gravitation. The Poynting-Robertson effect (*3*) is a well-known example of how even a very small nonradial force may accelerate an object toward the sun.

In a more advanced vehicle the electric power extracted from the wind may be used to operate a plasma propulsion engine. In this way a higher acceleration can be obtained and, at least in principle, propulsion in any direction will be possible. In other imaginable configurations the beam from the plasma engine, or auxiliary plasma or particle beams, may be used for current conduction, thereby avoiding many problems associated with a long and fragile cable that must be kept at a low temperature.

The ability of a plasma-emitting solar wind–powered vehicle to move also against the wind may seem paradoxical, but it is a simple consequence of the general laws of sailing. Since these laws seem to be little known and, since a short literature search has not turned up any suitable reference, it seems necessary to clarify some of the fundamental concepts.

Let us take, as the most general definition of sailing, the motion and propulsion of a vehicle without internal energy sources. According to this definition, a "sailing boat" thus may have all kinds of complicated machinery, the only requirement being that the energy for propulsion must originate from the media surrounding it. Furthermore, all cases for which the vehicle receives energy transmitted to it from any kind of man-made source are explicitly excluded.

Clearly the propulsion of a "sailing boat" originates from momentum interaction with the media around it. The case of a boat interacting with a single medium with constant flow velocity is trivial. Since the boat can derive its energy of motion solely from work done on it by the medium, it must move with one component of its velocity directed downwind. In complete agreement with Sonett, we conclude that to move upstream the boat would have to do work upon the wind, which, according to the definition above, is energetically impossible. This is the case of an iceboat without runners, as discussed by Sonett. In situations where the solar gravitation can be neglected, this explanation applies also to the solar wind vehicle propelled by the $\mathbf{I} \times \mathbf{B}$ interaction discussed above.

Far more interesting is the case of a boat interacting with two media having different states of motion. In this case the boat can extract energy by transferring momentum from one medium to the other, in a direction so as to equalize their states of motion. Quantitatively, the maximum possible energy gain is given by

$$\frac{dW}{dt} = v_{\mathrm{rel}} \cdot \frac{dp}{dt} \qquad (1)$$

where v_{rel} is the relative velocity of the two media and dp/dt is the momentum transfer effected by the vehicle. The extracted energy can be used to move the vehicle against the force fields associated with one or both of the media and to compensate for frictional losses associated with vehicle motion.

Equation 1 seems to be a very general relation covering a wide variety of phenomena, and the word "medium" may mean almost any force field. [As an example, the well-known Fermi acceleration mechanism (*4*), whereby a particle gains energy by interacting with two moving magnetic mirrors, follows directly from Eq. 1.] It can also easily be generalized to include the case where one of the media is originally inside the vehicle and successively ejected by some machinery. It may be disputed whether such a vehicle should be referred to as a sailing vehicle since its propulsion is possible only as long as matter is available for ejection. In a wide sense the name "sailing vehicle" may be justified, however, since the motion of the vehicle is governed by the law of sailing, Eq. 1.

Clearly, Eq. 1 replaces the simple energy relation governing the motion of a boat interacting with a single medium. Consequently, Sonett's requirement (i) is not applicable to the plasma engine type of solar wind vehicle, which interacts with two different media. Thus, no fundamental principle prevents a solar wind sailing boat of the plasma engine type from moving against the wind. Moreover, there is nothing fundamental about the fact that an ordinary sailing boat cannot go straight against the wind.

One can easily overcome this inability, for example, by supplying the energy from a wind-powered generator to a suitably dimensioned water screw. A suitably designed solar wind vehicle will, at least in principle, be able to move in any desirable direction. On the other hand, practical difficulties such as unacceptable "fuel" consumption or low efficiency for certain types of operation may very well be found to limit its usefulness.

The laboratory experiment proposed by Sonett is fully feasible, and a working table-top device could very well be constructed: An armature with a length of 1 m moving along rails with a speed of 10 m/sec across a field of 2000 gauss would generate a voltage of 2 volts. Let us assume a motor of internal resistance 0.2 ohm mounted in the center of the armature and connected in series with the rest of the loop which may have a considerably lower resistance. The current will then be 10 amperes and the motor will develop 20 watts. The motor is used to drive a piston forcing water (from an internal tank) through a nozzle.

If we may assume a motor efficiency of 80 percent, we can eject 500 g/sec at a speed of 8 m/sec relative to the armature. The propulsive force so produced will be 4 newtons as compared to the electrodynamic drag of 2 newtons. Losses higher than those assumed here could be overcome at the cost of increased "fuel" consumption by the choice of a lower exhaust velocity. A net force of 2 newtons is not very impressive, but the scaling laws are very unfavorable for the model. (The drag is here proportional to the velocity, the propulsive force to its square.) The device will not be able to start from zero velocity, a limitation which is also understandable from Eq. 1, where v_{rel} now stands for the relative velocity of the two media "water" and "the rail system." Once given sufficient velocity, however, the "vehicle" will be able to propel itself and even accelerate. This represents no perpetual motion machine, however, since the motion will stop when all the "fuel" has been ejected. The energy is available initially as the kinetic energy of the water, and the energy of the total system decreases steadily during the motion.

Alternatively, the device could start from zero velocity if the rail system were instead moving. Seen from a reference frame attached to the armature, an electromotive force will then be induced in the shorting section at the end of the rails. This potential will drive a current through the armature and the motor, thus producing motion.

Let us turn now to the real solar wind vehicle. An evaluation of its capabilities involves a certain amount of guesswork. For a solar wind electric field E, the highest potential difference that can be tapped by a wire of length L is EL. A field of 2 mv per meter and a 500-km cable would give 1 kv. By suitable arrangements at the ends of the cable a current I is made to flow through the cable. From laboratory experiments it is known (*5*) that vacuum arcs of many kiloamperes strength can burn with voltage drops as low as 10 to 25 volts. Similarly, a plasma jet can be expected to conduct considerable currents with quite moderate voltage drops. Therefore, a current of the order of 1 ka does not seem unrealistic. The power so extracted is used to operate the plasma propulsion engine. Assuming that a fraction η of the total power IEL can be transferred to the translational energy of a plasma beam, we have

$$\eta IEL = \frac{1}{2} q w^2 \qquad (2)$$

where q is the mass emitted per time unit and w is the ejection velocity.

The propulsive force so produced is

$$F_{\mathrm{prop}} = qw = \frac{2\eta IEL}{w} \qquad (3)$$

The electrodynamic drag finally will be $f \cdot IBL$, where f is a factor that may be larger than unity if the solar wind magnetic field is piling up in front of the cable. It is not certain that this will be the case since the cable and the volume occupied by the magnetic field of the current I is thin as compared to the ion gyro radius.

It is at present difficult to comment in detail on the effects of the flow field interaction on the extractable power and the drag force. Equation 1 seems to indicate that they should vary in approximate proportion to each other, but part of the power may possibly leak through the compressed plasma in front of the cable. Detailed studies and experiments will be necessary before the exact values of η and f can be stated. Since the "source impedance" of the solar wind plasma and the cable hopefully will be much lower than that of the plasma engine, the power reduction by a factor of 2 (or 4) foreseen in Sonett's discussion is not explicitly taken account of. The factor η of Eq. 2 may be taken to include such effects as well, if important.

The net force when the vehicle is flying against the wind is found by combining the previous expressions and $E = vB$, where v is the solar wind velocity:

$$F_{\mathrm{net}} = IBL \left(\frac{2\eta v}{w} - f\right) \qquad (4)$$

From Eq. 4 it follows that we can always beat the solar wind by using an exhaust velocity

$$w < \frac{2\eta}{f} v$$

Since v is of the order of 400 km/sec, it is obvious that a considerable reduction of efficiency can be afforded before the exhaust velocity, and thus also the "fuel" economy, becomes comparable to that of a conventional rocket.

A study of a solar wind vehicle where a long plasma beam is instead used as current conductor leads to similar conclusions. The success of such a vehicle also depends critically upon the feasibility of long, well-confined plasma beams. We will not comment on this idea any further here.

The question of the ability of a vehicle to move against the wind as discussed here may be largely academic. Most long-range space in the foreseeable future flights will certainly be unmanned, and, when it sometimes becomes desirable to bring back a vehicle, this can often be done by propelling the vehicle at right angles to the solar direction so as to decrease its orbital angular momentum. When this is done, gravitation will quickly bring the vehicle back. Certainly far more important is the ability of a propulsion system to offer a reasonable acceleration in combination with an acceptable fuel consumption. Although it is too early to state the merits of solar wind sailing, it seems to offer sufficient possibilities to encourage further studies.

Note added in proof: We have just learned that some of the ideas proposed in (*1*) and (*2*) have already been discussed by Moore (*6*). Our results are in general agreement with those of Moore, and we regret very much our ignorance of his work.

ULF FAHLESON
HANNES ALFVÉN*
Department of Plasma Physics, Royal Institute of Technology, Stockholm, Sweden

References and Notes

1. H. Alfvén, *Science* **176**, 167 (1972).
2. U. Fahleson, *Roy. Inst. Technol. Stockholm Rep. TRITA-EPP-72-04*, in press.
3. H. P. Robertson, *Mon. Notic. Roy. Astron. Soc.* **97**, 423 (1937).
4. E. Fermi, *Astrophys. J.* **119**, 1 (1954).
5. J. C. Sherman, personal communication.
6. R. D. Moore, paper 66-257 presented at the American Inst. of Aeronautics and Astronautics 5th Electric Propulsion Conf., San Diego, Calif., 7–9 Mar. 1966; paper 66-596 presented at the American Inst. of Aeronautics and Astronautics 2nd Propulsion Joint Specialist Conf., Colorado Springs, Colo., 13–17 June 1966.

* Present address: Department of Applied Physics and Information Science, University of California, San Diego, La Jolla 92037.

26 September 1972

Time Reversal and Irreversibility

Sachs (*1*) has presented a thought-provoking article on time reversal. However, I find that his introductory arguments regarding the "flow of time" and the origin of irreversibility are somewhat captivated by traditional thinking in statistical mechanics. Among other things, the author states that irreversibility is introduced in the averaging process over the detailed molecular motions.

In a previous article (*2*) I demonstrated that the introduction of statistics does not by itself produce irreversibility. The origin of irreversibility, time asymmetry, or the law of increasing entropy, as given by any of the statistical mechanical "theorems," is not to be found in the mathematical formulations, but rather in an a priori choice made by the statistical physicist of a probability that is actually asymmetrical in time. This can be related to the empirical fact that blind statistical prediction is "physical," whereas blind statistical retrodiction is not. Thus, one can calculate the probability that something physical will happen, but not the probability that something physical did happen. This should be recognized as an imposed direction of time or an imposed initial condition on symmetric probability theory. It is a selection which is usually undeclared but which is essentially equivalent to an a priori introduction of the essence of irreversibility (and the so-called second law) into what is widely (and wrongly) believed to be a deduced statistical time asymmetry, statistical law of the increase of entropy or mixing, and so forth. Consequently, I stress that statistical (classical or quantum) mechanics fails to deduce the origin of irreversibility and time anisotropies in nature.

Without any other convincing arguments as to the origin of irreversibility, an increasing number of scientists are now convinced that the only explanation presently acceptable is that of the new astrophysical school of thermodynamics (*2–4*). Also, weak violations of the invariance of the laws of motion under time reversal (T-invariance) or space reversal and charge conjugation (CP-invariance) can now be explained by the astrophysical school (*2, 4, 5*).

My last remark is related in part only to semantics. The use of the conception flow of time has in the past produced logical havoc for physics. This conception also vitiated Bridgman's objections to Eddington's thermodynamic account of the anisotropy of time (*6*). The term flow of time should be replaced by a term such as anisotropy of time.

I stress that these remarks do not affect the contribution of Sachs' article. I hope that it will provoke all of us to reexamine the "fundamental" concepts in some of our theories.

BENJAMIN GAL-OR
Technion-Israel Institute of Technology, Haifa

References

1. R. G. Sachs, *Science* **176**, 587 (1972).
2. B. Gal-Or, *ibid.*, p. 11.
3. ———, 1971 Scientific Award Paper, *Ann. N.Y. Acad. Sci.*, in press.
4. ———, in *Entropy and Information in Science and Philosophy*, J. Zeman, Ed. (Elsevier, Amsterdam, in press).
5. ———, in *Modern Developments in Thermodynamics*, B. Gal-Or, Ed. (Technion-Israel Institute of Technology, Haifa, in press).
6. A. Grünbaum, in *The Nature of Time*, T. Gold and D. L. Schumacher, Eds. (Cornell Univ. Press, Ithaca, N.Y., 1967), p. 149.

17 July 1972

Gal-Or's reference to the statement that "irreversibility is introduced in the averaging process over the detailed molecular motions" takes it out of context. I introduced the concept of averaging to give a loose definition of the macroscopic (thermodynamic) variables of a complex system in terms of the microscopic motions, which are reversible. My complete statement places the emphasis on the incredibly small probability for attaining the initial conditions required for exact reversal of the motion if one can fix only the macroscopic conditions.

This emphasis on the role of initial conditions, which is to be found throughout my discussion, does not seem to be in disagreement with Gal-Or's remarks. However, I do disagree with his suggestion that there is a time asymmetry to be explained. If a complex system is initially in an ordered state, the probability is overwhelming that it will behave symmetrically in time; that is, if the detailed microscopic motions are followed either forward or backward in time from that initial moment, the corresponding thermodynamic variables determined by averaging over the particle motions will change irreversibly.

My article is not intended to be a discussion of the laws of irreversible thermodynamics. My only purpose in bringing up the subject at all is to show, in as naive a way as possible, that there is no contradiction between the time reversal invariance of the laws of motion and irreversibility of the variations of the thermodynamic variables.

Although my arguments may be "captivated by traditional thinking," they are given in connection with a traditional problem in physics which yields to traditional answers. The problem arises not in trying to determine the answers but in trying to phrase them in terms suitable for a wider audience.

ROBERT G. SACHS
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637