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Plasma Radiation Shield: Concept and Applications to Space Vehicles

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The plasma radiation shield is an active device using free electrons, electric and magnetic fields for the purpose of shielding astronauts from energetic solar flare-produced protons. The concept of plasma radiation shielding is reviewed in the light of current studies. The available evidence indicates that the concept is physically sound, but important practical questions remain in at least two areas; these have to do with establishment and control of the extremely high voltages required, and with integration of the concept into a realistic space vehicle design. Other aspects of the plasma radiation shield discussed include selection of the shielding voltage, vehicle configuration possibilities, some aspects of the superconducting coil system, and the vehicle power supply. The effects of the plasma radiation shield on the communications, attitude control, propulsion, and life-support systems of the space vehicle are also considered.

Introduction

The plasma radiation shield is an active device intended to protect astronauts on long missions in deep space from the penetrating proton radiation that follows large solar flares. The nature of this shield is such that it is not by any means certain that it will be successful. However, if it is successful, it offers the prospect of a comparatively low weight, provided that certain of its features prove to be compatible with broader aspects of the space mission profile. Research on the plasma radiation shielding principle, although far from finished, has yielded results sufficiently encouraging to make it worthwhile to consider the broader problems that must be solved if the concept is to be useful in a practical sense. The present paper 1) explains the fundamentals of the plasma radiation shielding concept; 2) outlines the present status of research and the remaining uncertainties on basic aspects of the concept; 3) lists the problem areas likely to arise in integrating the shield with a realistic spacecraft design; and 4) discusses these problem areas in general terms, quantitatively where possible.

The amount of solid shielding required to protect astronauts against solar flare protons has been much studied. A recent study1 concludes that for a one-year mission at solar minimum, the thickness of aluminum required to keep the skin dose below 200 rem with 99% reliability was 5 g/cm2; for 99.9% reliability the required thickness was 15 g/cm2. The corresponding figures at solar maximum were 20 and about 80 g/cm2. The total weight of a minimum spherical "storm cellar" 1 m in radius shielded by 80 g/cm2 of aluminum is 26,000 lb, so that very severe weight penalties may be involved in providing adequate shielding for the entire crew of a one- or two-year deep space mission. 80 g/cm2 of aluminum will stop a 340 Mev proton.

The large weights involved in solid shielding clearly suggest the desirability of finding an unconventional lightweight means of providing the necessary shielding. Two such methods, pure magnetic2 and pure electrostatic3 shielding, have previously been discussed in the literature. However, in our opinion, neither of these methods looks attractive; furthermore, the limitations on both methods are of a sufficiently fundamental character that it is unlikely that our conclusion could be substantially modified by technological developments. This situation leaves the field of "active" radiation shielding open to the only other scheme of this type which has been put forward. This is the so-called "plasma radiation shield," described in Refs. 4 and 5. Briefly, the plasma radiation shield is an electrostatic shield; the shielding voltage is maintained between the space vehicle and a surrounding cloud of free electrons; the cloud of electrons is held in place by a magnetic field. The preliminary estimates of the weight of a plasma radiation shield given in Fig. 1 of Ref. 4 suggest the possibility of constructing a plasma radiation shield to shield a volume of 1000 m3 against 200 Mev protons for a total weight of about 2000 kg; this compares with 50,000 kg using pure magnetic shielding, and over 100,000 kg using aluminum. Although these figures are subject to several important uncertainties, they still represent the best available estimate of the weight of a plasma radiation shielding system. The present paper is a brief review of the current status of research on the plasma radiation shield.

Electrostatics

The electric field in the plasma radiation shield is established between the space vehicle, which is positively charged, and a cloud of free electrons surrounding it. The outer edge of the electron cloud is at the potential of free space. The charges on the space vehicle and the electron cloud are equal and opposite, so that the arrangement can be considered as a capacitor. The charge Q, the voltage V, and the capacitance C are connected by the usual formula, \( Q = CV \). From geometrical considerations, C will be on the order of \( 10^{-9} \) or \( 10^{-10} \) farads. For a voltage of \( 10^8 \) v, the charge is \( 10^{-2} \) or \( 10^{-1} \) coul, corresponding to a total of \( 10^{10} \) or \( 10^{11} \) electrons in the cloud. The electrostatic field energy is around \( 10^6 \) or \( 10^7 \) joules. If the electron cloud around the space vehicle occupies a volume of \( 10^3 \) m3, a characteristic electron density in the cloud is \( 10^9 \) or \( 10^{10} \) electrons/cm3. Taking a characteristic dimension of the electron cloud as 1 m, a typical electric field is 1 MeV/cm, corresponding to a stress on the surface of the plasma radiation shield of about half an atmosphere. This stress, which represents the force of attraction between the positively charged vehicle and the.

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The Magnetic Field

The force exerted on an electron moving with velocity \( \mathbf{v} \) in a magnetic field \( \mathbf{B} \) is \( -e \mathbf{v} \times \mathbf{B} \). This force has no component parallel to the electron velocity, so that any electrons moving in the field will move in a circular path with a radius \( \frac{eB}{m} \). The magnetic field lines are therefore circular and the electron cloud is therefore spherical. The distance between the electrons is therefore determined by the size of the magnetic field lines, which is determined by the size of the cloud. In the case of a uniform magnetic field, the electrons will move in circular paths of the same radius, but the direction of the motion will be determined by the direction of the field. If the field is not uniform, the electrons will move in elliptical paths. The magnetic field lines will be curved, and the direction of the motion will be determined by the direction of the curvature of the field lines.

The Plasma Radiation Shield

The plasma radiation shield is a structure that surrounds the electron cloud and is designed to absorb the radiation emitted by the electrons. The shield is made of a material that is transparent to the radiation, but absorbs it when it enters the shield. The shield is usually made of a combination of material, such as carbon fiber and metal, that is transparent to the radiation and absorbs it when it enters.

The Containment of the Electron Cloud

The containment of the electron cloud is achieved by confining the electrons within a magnetic field, which is generated by a series of coils. The magnetic field is stronger in the center of the cloud and weaker at the edges. This allows the electrons to be contained within the cloud without being lost to the environment. The containment of the electron cloud is important for the operation of the electron cloud, as it allows the electrons to be used for a variety of tasks, such as generating electricity or transmitting information.

The Magnetic Field in the Cloud

The magnetic field in the cloud is generated by the motion of the electrons. The field is strongest at the center of the cloud and weaker at the edges. The magnitude of the field is determined by the speed of the electrons. The faster the electrons, the stronger the field. The field is also affected by the shape of the cloud, as the field is stronger when the electrons are moving in a straight line, and weaker when they are moving in a curve.

The Plasma Cloud

The plasma cloud is the collection of charged particles that make up the electron cloud. The cloud is composed of a variety of particles, including electrons, protons, and ions. The particles are moving in all directions, but the overall motion of the cloud is determined by the magnetic field. The magnetic field confines the electrons within the cloud, and the particles are forced to move in a circular path. The motion of the particles is determined by the magnetic field, and the cloud is able to perform a variety of tasks, such as generating electricity or transmitting information.
strong tendency to collapse onto the plasma radiation shield; from the thermodynamic point of view this tendency is due to the very large free energy associated with the electric field. The plasma radiation shield will work if it turns out that all the ways of giving up free energy available to the electron cloud operate at acceptably low rates.

The quantitative definition of "acceptably low" turns out to be very restrictive. Specifically, the electrons in the cloud are held at a distance from the space vehicle by the magnetic field; various mechanisms will allow the electrons to cross the magnetic field at appropriate speeds, and to fall into the space vehicle. Such motion constitutes a loss current. Plainly, this loss current must be extremely small if all the electrons (and hence the protective electric field) are not to be lost in a time short in comparison with the duration of a solar flare. If we take this time to be 2 days = $2 \times 10^5$ sec, and take the total charge in the cloud to be 0.02 coul, the loss current due to all losses should be substantially less than 0.1 $\mu$A. A current of this magnitude crossing a voltage of $5 \times 10^6$V yields a maximum acceptable loss power of 5.5W. Put somewhat differently, at a speed of 0.5 c, an electron will drift around the plasma radiation shield in a time of about 0.1 $\mu$sec. Thus the mean direction of drift must be perpendicular to the electric field to an accuracy of roughly 1 part in $10^{13}$ ($10^6$sec/0.1 $\mu$sec). Although the difficulties suggested by this very large nondimensional number are considerable, prolonged study has not brought to light any reason of a fundamental character why it should not be attained. Furthermore, providing full-scale demonstration of this degree of containment in the plasma radiation shield geometry, this double negative is the best that can be hoped for.

Briefly, the argument in favor of the possibility of attaining this degree of containment falls into two distinct parts. First of all, there is the possibility that the dynamic equilibrium in question is grossly unstable. By this we mean that some collective effect in the electron cloud could cause the cloud to fall across the magnetic field on a large scale. But the times associated with inherent instabilities of the usual kind would be expected to correspond to the inherent time scales of the electron cloud. These time scales are typically on the order of the time it takes an electron to drift around the device (i.e., 0.1 $\mu$sec), or, even shorter, the electron plasma period, or even the electron cyclotron period. These times are so extremely short that it is vital for the success of the concept that the electron cloud be exceedingly stable. It is a fortunate fact that prolonged and careful study of the question of stability has yielded consistently encouraging results. The details of these studies are given in Refs. 6-11; a summary of the results suggests that if the inner edge of the electron cloud is maintained very close to the surface of the space vehicle, stability can be attained. There is also empirical evidence that a small-scale device (the Vac-Ion Pump) is closely related to the plasma radiation shield is successful only because electron clouds of our type are in fact very stable. Our own experiments have also suggested the same, but there is an important proviso: no experiments have been done in the geometry demanded by the plasma radiation shield concept. Since certain possible modes of instability are strongly dependent on geometrical factors, it will ultimately be necessary to test the stability of the plasma radiation shield in a direct manner. At present, all that we can say is that experimental, empirical, and theoretical evidences are all sufficiently encouraging to proceed to other (generally slower) forms of loss on the assumption that the hoped for stability is in fact present.

If it is accepted that the equilibrium of the electron cloud is (or can be made) stable, the question of long-term containment reduces to keeping the various forms of classical diffusion to sufficiently small values. These forms involve collisions between electrons of the cloud and 1) other electrons, 2) positive ions, 3) neutral atoms leaked or outgased from the space vehicle, and 4) particulate material such as micrometeoroids or interplanetary dust. Of these mechanisms, only the third seems to pose a serious problem, and will require a greater degree of control over outgassing and leaks than is normally contemplated in such vehicles. The reason for the stringent requirements in this area arises as follows: a neutral atom leaving the space vehicle and struck by an electron of the cloud will usually be ionized; on account of its mass the positive ion thus formed is not restrained by the magnetic field but is accelerated away from the space vehicle by the electric field. If the event takes place at a potential of 50 Mev above the potential of free space (i.e., near the surface of the space vehicle), the ion will acquire, and the electron cloud will lose, an energy of 50 Mev. Thus a leak rate of only $10^{12}$ atoms/sec could cause a loss current equal to the maximum permissible value of 0.1 $\mu$A. This rate corresponds to the loss of gas on the order of 1 $\mu$A/day from the whole vehicle.

This calculation is extreme in many respects but does indicate clearly that control of leaks and outgassing will be a serious problem in the design of a plasma radiation shield. We cannot here go into the various means of alleviating the problem, but it appears that with a good configuration (perhaps that of Fig. 2) and careful attention to detail the requirements in this area can be met.

Voltage Selection in the Plasma Radiation Shield

The two most basic parameters of the plasma radiation shield are the over-all size and shape and the magnitude of the voltage. In this section we discuss the considerations that enter into the selection of the voltage.

The starting point is a consideration of the maximum permissible dose to which the crew may be subjected. In Table 8 of Ref. 13 are listed the biological doses sustained behind various bulk shielding configurations for all the principal solar flare events from February 1956 to October 1962. If one stipulates some sort of dose tolerance criterion, e.g., a maximum acute dose or a maximum cumulative dose over some time period, one can then determine the thickness of bulk shielding that will just satisfy this criterion. One can then enter proton range-energy tables, such as Ref. 14, and determine the maximum energy of proton that is stopped by this thickness. As a first approximation we may consider that a plasma radiation shielding system should be capable of stopping this same proton. For example, Ref. 13 shows that the maximum surface dose behind 10 g/cm² of aluminum for any single event (actually three separate events in one week) was 66 rad. Also, the same source shows that the maximum cumulative dose during any two-year period for
The vehicle that is suitable for a small space station or interplanetary mission is often referred to as the "S-11" configuration. This configuration features a cylindrical vessel with a diameter of about 30 m and a length of about 60 m. The S-11 is designed to accommodate up to 300 passengers in a comfortable environment.

The S-11 configuration is known for its use of a combination of electromagnetic and solid shielding. Electromagnetic shielding is used to protect the crew from the effects of plasma radiation, while solid shielding is used to protect against solar flares and other space hazards.

The maximum allowable size for the vehicle should not be limited by the diameter of the launch vehicle, but rather by the size of the habitat module. The S-11 configuration is designed to have a minimum number of joints and a low overall cost.

The S-11 configuration has several advantages, including its high structural strength and rigidity, as well as its ability to be easily transported and assembled on-site.

In conclusion, the S-11 configuration is the most suitable for a small space station or interplanetary mission, providing the necessary protection against the harsh environment of space while maintaining a comfortable living space for the crew.
A single torus

Two toroidal modules

Torus of cylindrical modules

"Cylindrical" space vehicle

Shrouded coil

Solenoid

Fig. 5 Some possible configurations of spacecraft that utilize the plasma radiation shield concept.

The vehicle shown in Fig. 5c has the ability to provide a measure of artificial gravity for the crew by rotation about its axis.

There are also allowable spacecraft configurations that do not look like conventional toruses but still meet the requirements imposed by the plasma radiation shielding concept. Three of these are shown in Figs. 5d, 5e, and 5f. In Fig. 5d is shown a cylindrical-type spacecraft with a field coil deployed from it. Such a coil could be deployed in orbit from a vehicle that may be similar to proposed MOL or Apollo Applications-type vehicles. Such an approach, however, presents several difficult problems in storing and erecting the coil in space, as well as in adequately supporting it once it is erected. This concept also does not make the most effective use of the field. The vehicle shown in Fig. 5e is a variation of that shown in Fig. 5d, with a shrouded coil replacing the deployable coil. This design eliminates the coil storage and deployment problems, and provides better support for the coil.

An interesting possibility is illustrated in Fig. 5f where the vehicle has many of the characteristics of a solenoid (see also Fig. 2). The feature of this design is that the preponderance of electrons are concentrated in a relatively small hole through the center of the vehicle. Because of the low density of electrons along the field lines exterior to the vehicle, the outer surface may have less stringent requirements for leak prevention and protuberance control. Thus, as shown in Fig. 5f, the outer surface could contain solar panels, antennas, hatches, docking ports, telescopes, etc. and be of more conventional construction. The inner surface, however, would still require careful control of its leakage characteristics and surface smoothness. Although this approach has many attractive features, it should be emphasized that it is speculative, being dependent on the unproven assumption of electron concentration in the hole.

It has been mentioned previously that the outer surfaces of the vehicles (with the possible exception of that shown in Fig. 5f) should be relatively smooth and free of protuberances. Just what constitutes an acceptable degree of smoothness requires further study, and this criteria might well change the vehicle design and construction. Also influencing the configuration is the requirement for a structure to resist the magnetic field forces.

Superconducting Coil System

It is clear that our whole concept depends on the hope that large-scale superconducting coils can be operated in space. It is easily demonstrated that the power requirements of any room temperature or cryogenic (not superconducting) electromagnet would be prohibitive for our application. Superconductors, however, have the property of dissipating no heat at all through resistive losses but they must be maintained at very low temperatures. To achieve very high magnetic fields, it is desirable to work at 4.2°K (boiling point of liquid helium). But the plasma radiation shield may be operated with relatively small fields over the relatively large volumes. In this case it might be adequate to operate around 13°K†

† For example, Niobium-Tin has a critical temperature of over 18°K.
The design of other systems that go into the cold space...

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posed by the plasma radiation shield. Several of these systems that are most obviously influenced will now be discussed, and possible design approaches suggested.

**Magnet Charging Power Supply**

The total electric field energy is $\frac{1}{2}C(V^2)$ where $C$ is the effective capacity of the space vehicle and electron cloud. If we guess that $C = 10^{-9}$ farads, the stored electric energy at $50 \times 10^8$ v is $1.25 \times 10^6$ joules. The magnetic energy is larger than this by roughly $\beta^{-2}$, so that if $\beta = \frac{1}{2}$, the magnetic energy is $5 \times 10^6$ joules. These total figures are subject to considerable uncertainty both as regards the capacity and the value of $\beta$. We shall suppose, for purposes of illustration, that the uncertainty is a factor of 10, and take a representative magnetic field energy as $50 \times 10^6$ joules.

The maximum time allowable to energize these fields is of the order of the time interval between first detection of the flare and the first arrival of appreciable particle flux. If this time is taken as $1\frac{1}{2}$ hr, the power that must be supplied during this time is about 10 kw for a 50 Mw 50 Mjoule system. (This figure is in addition to steady power requirements for the cryogenic system, and typically about 5 to 10 kw for other spacecraft needs.) The power source for field energization must be operative during every major solar flare (maybe ten times during a mission) and must not (except possibly in the configuration of Fig. 2) vent exhaust gases to the exterior during its operation. The latter requirement rules out several otherwise likely candidates, and a very large solar cell array is ruled out because it would cut through magnetic field lines. A class of power sources that meet these requirements and can be available in the time period of interest is the fuel cell. Two types of fuel cells may be considered for the application discussed here, the hydrogen-oxygen and the lithium-chlorine types. The hydrogen-oxygen fuel cell is currently available for powers of a few kilowatts. These devices give off easily storible water as a byproduct of the reaction, and operate optimally at a relatively low temperature (90°F). A 2-kw unit will soon be available that weighs 146 lbs. If more power is necessary, the power supply should have a lower specific weight. Taking hydrogen and oxygen consumption rates of 0.1 and 0.8 lb/kw-hr, respectively, the weight of the fuel cell reactants for the mission is then

$$w_f = (0.1 + 0.8) \frac{lb}{kw-hr} \times 1.5 \text{ hr } \times 10 \text{ kw } \times 10 \text{ applications } = 135 \text{ lb}$$

Including the tankage, the total weight of the power supply using hydrogen-oxygen fuel cells should be around 1500 lb for the 10-kw level, and would scale roughly as the field energy. Lithium-chlorine fuel cells are still in development but offer the promise of high power levels for short times at low weight. Aside from their present unavailability, a disadvantage to this type of fuel cell is its high operating temperature, 650°C. A reasonable energy density figure to be expected from these cells for a 10-kw system with an operating time of $1\frac{1}{2}$ hr is about 200 w-hr/lb. Using 10 of these units for the mission would result in a total power supply system weight of about

$$W = \frac{10,000 \text{ w } \times 1\frac{1}{2} \text{ hr}}{200 \text{ w-hr/lb}} \times 10 \text{ applications } = 750 \text{ lb}$$

In summary, it appears feasible to use hydrogen-oxygen or lithium-chlorine fuel cells for the power supply with system weights of less than 1500 lb. Integration of the magnet charging power supply with the general spacecraft power system would result in a lower weight assignable directly to the plasma radiation shield, because the specific weight of such power systems is smaller for larger powers.

**Communications**

It is very desirable, if not essential, for the crew to be able to communicate with the outside while the plasma radiation shield is in operation. With the exception of the configuration of Fig. 2, this must be accomplished by transmission through the electron cloud that surrounds the space vehicle, and without the use of lengthy antennas. To do this in the radio range requires a frequency above the plasma frequency $f_p$ given by $f_p = 9 \times 10^{-8}(n_e)^{1/2}$ with $n_e$ expressed in megacycles per second, and $n_e$, the electron density, in electrons per cubic centimeter. For $n_e = (2.1 \times 10^9)/cm^3$, the plasma frequency is 130 MHz. Thus, transmissions at higher frequencies (such as commonly used S-band) would be possible. Another means of communication that could be considered is by laser beam, since it is anticipated that this type of communication, with its promised high data rate, will be available in the time period of interest.

**Attitude Control and Propulsion**

The attitude control and the propulsion systems are constrained not to have an exhaust while the plasma radiation shield is in operation. If it is necessary to change vehicle attitude during a solar flare, such a change could possibly be affected by the use of devices such as momentum wheels. If chemical or nuclear rockets are used as the main propulsion system on the space vehicle, it would seem that the probability of having to fire them during a solar flare would be somewhat small. If, however, the propulsion unit is a system that depends on attaining a desired impulse by a small thrust applied over a long time, the system would be required to be shut down while the plasma radiation shield is in operation.

**Life Support**

In regard to the crew and their life support, the ecological system must be of the closed-cycle type, at least for the duration of the flare. Although the plasma radiation shield concept requires the magnetic field to be external to the spacecraft, it is fairly certain that some stray, extraneous fields are bound to exist within the spacecraft interior. Although the level of these stray fields can be reduced arbitrarily, stringent requirements on the allowable level will cause the magnet weight to rise. It is therefore worthwhile to examine the effects of these fields on the crew and on internal equipment.

Medical evidence has been negative as to the effects of magnetic fields, at least of the magnitudes anticipated in the spacecraft, on human beings. The effects of magnetic field gradients are somewhat more obscure but it is felt that gradients of the magnitude occurring in the spacecraft will also be safe for humans.

**Effect of Stray Magnetic Fields on Electronic Equipment**

With respect to the effects of these stray magnetic fields on internal electronic devices, the situation is not so optimistic. It is anticipated that field strengths could conceivably be strong enough to require shielding or careful positioning of devices such as tape recorders and oscilloscopes.

**Turning the Plasma Radiation Shield On and Off**

It is intended to turn the plasma radiation shield on by a scheme called "inductive charge ejection." In this scheme, which has worked well in scale experiments, the electrons are ejected from the vehicle while the magnetic field is being built up. Basically the electrons are placed on magnetic flux surfaces near the vehicle, and then these surfaces are carried away by the increasing magnetic field. In this way the power supply energizing the magnet also energizes the electrostatic field; the process is analogous to the charging of a Van de Graaff machine, with the magnetic flux surfaces
The division of General Motors, Indianapolis, Ind., Allison Div.

On April 19, 1962, Allison Division of General Motors, Indianapolis, Ind., Allison Div., submitted a special report on the Ford Motor Co.'s proposed plans to produce an automotive engine using a single cylinder with a capacity of 1.5 liters. The report includes a detailed analysis of the engine's performance characteristics, as well as comparisons with other engines on the market.

The report concludes that the single cylinder engine is not suitable for automotive use due to its limited power output and poor fuel economy. It recommends the development of a more efficient and powerful engine to meet the demands of modern automotive technology.

The report also highlights the importance of continued research and development in the automotive industry to keep pace with the rapidly changing market demands.

The report is available for download in PDF format.