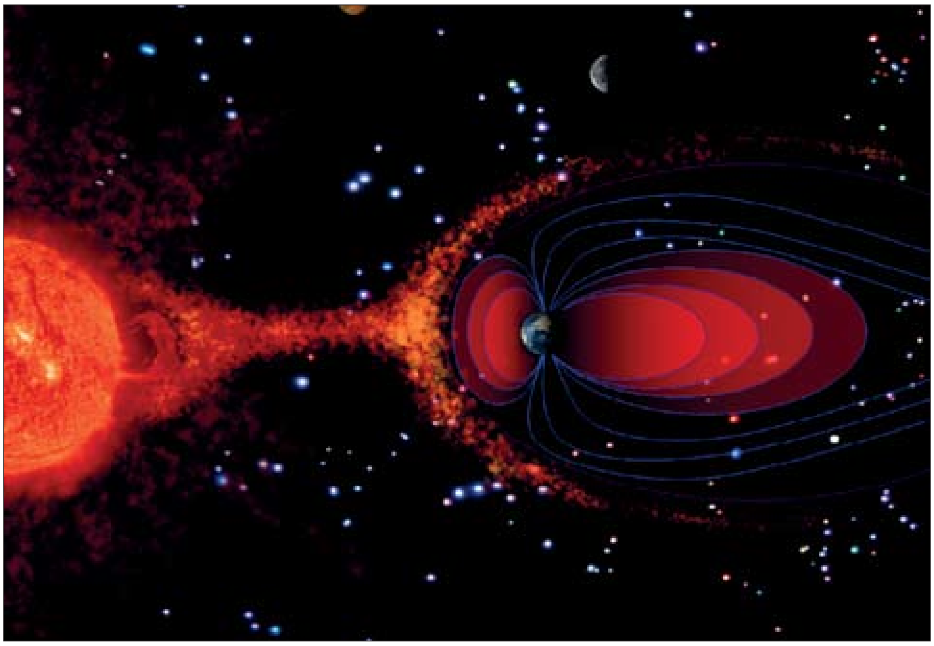
Shields for the sta

Ruth Bamford, Robert Bingham and Mike Hapgood discuss the physics behind shielding spacecraft from solar and cosmic radiation with mini-magnetospheres.



1: The Earth's magnetic field extends out into space to form the magnetosphere, which deflects the hazardous energetic plasma of the solar wind, leaving our planet sitting like a pebble in a stream.

Abstract

A renewed interest in human space exploration demands renewed care for the safety of astronauts venturing far from Earth's protective magnetosphere. Here we assess possible mechanisms for the active shielding of a spacecraft, with consideration of scale, effectiveness and power use. Although nothing yet exists to match the apparent simplicity and effectiveness of the shields shown on *Star Trek*, the physics of plasmas demonstrates that some useful form of shielding should be possible in the next few decades.

After more than three decades, space exploration is again on the agenda, with the distinct possibility of manned missions to the Moon and Mars within a few years. And this is where the trouble starts: space is a really dangerous place for humans to explore. There are the obvious dangers of blasting off the Earth on tons of liquid explosives in a tin can carrying all your own air, food and water. Coupled with this is the essential ability to know exactly where you are in three dimensions, over vast distances, through complex manoeuvres, before you even attempt the delicate business of re-entry. However, we have become quite adept at solving those problems over the past 50 years, and are confident enough to go to the Moon to stay and then move on to Mars. The problems in going further and staying longer are logistical and demand optimized engineering capabilities, but solutions can be envisioned, given the funds. But there is a potential show stopper – a hazard that has not been addressed since the Apollo Moon missions. This is the effects of solar and cosmic radiation. Space may appear to be a calm empty void, but in reality it is teeming with energetic particles and cosmic rays that have devastating effects on human tissue, and on DNA in particular.

With the exception of Apollo, all manned space activity has been close to the Earth, at less than 600 km altitude. This means that it is still within the Earth's ionosphere and within a tenuous atmosphere. So how is going to the Moon or Mars any different from spending 18 months on the International Space Station? Space is space, right? Wrong. "Space" between astronomical bodies is *mostly* empty vacuum by terrestrial standards, but it is the very lack of matter that means that energetic particles can be accelerated further and travel unattenuated. The energies the particles reach are so high that the atoms are mostly stripped of their electrons and travel as a quasi-neutral collective of negatively and positively charged particles connected together by electric and magnetic forces – a state of matter defined as a plasma. The particles are electrons and protons, predominately, though there are a few heavier elements. Although there are relatively few particles, their energies can be so high that they blast through DNA like a cannon ball – bringing radiation sickness and even death to astronauts. They don't do instrumentation much good either.

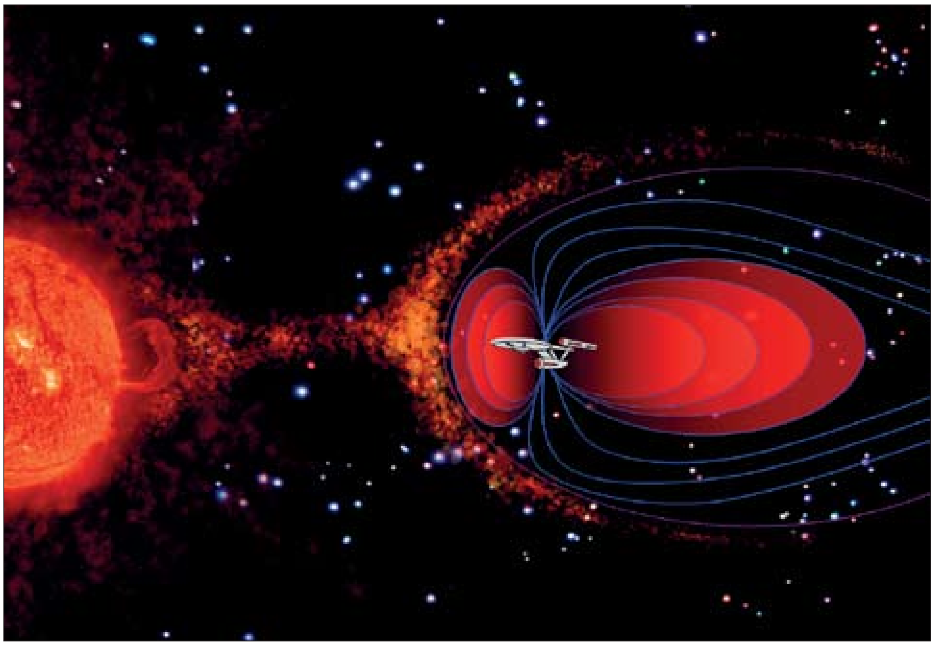
Close to the Earth we have additional protection from radiation in the form of the Earth's atmosphere and magnetosphere (figure 1). It is the presence of this "shield" that has enabled manned space programmes to avoid dealing with this problem so far. But they have to tackle it now if we are to venture to the Moon and Mars, outside the magnetospheric protection.

So why not bring a portable magnetosphere along with you into the solar system? It seems a pretty obvious solution. Future spacecraft and/or Moon bases could perhaps have portable "mini-magnetospheres" of their own to protect the inhabitants and electronics from the potentially lethal energetic particles from the Sun and outer cosmos. We need to determine the physics of a magnetospheric shield: Does a magnetosphere have to be the size of a planet in order to work? Could it work in miniature? And is it technologically practical to even consider on a spacecraft? This may all sound too like science fiction, but then again so did mobile phones 30 years ago.

More than one solution

The obvious and simple-sounding solution is to shield the occupants and electronics of a spacecraft behind thick absorbing walls. A planetary body offers the possibility of underground bases, though risks during EVAs remain – and there is little point establishing a planetary base just to stay indoors all the time. But it is during the journey in free space, fully exposed to the solar energetic particles, that the protection is most needed. It is here that the material solutions have a problem with extra weight, although that may have to be considered a necessity. But material shields have to be carefully designed if they are not to make matters worse. Energetic particles hitting a material shield can generate secondary

rship Enterprise



2: A conceptual illustration of a spacecraft, in this case the SS Enterprise, protected from a coronal mass ejection from the Sun by a deflector shield, thus keeping the human crew within safe.

radiation as they lose energy by colliding with nuclei in the material shield. This secondary radiation is potentially very dangerous as its lower energy particles have a great propensity to deposit their energy in human tissue. The shield must be thick enough to reduce secondaries to an acceptable level.

Medical solutions are another approach, and one with potentially far-reaching contributions to human health on Earth. NASA takes them very seriously. Frank Cucinotta, chief scientist for NASA's Radiation Research Program at the Johnson Space Center, recently said to *Physics World:* "We should be able to develop biological countermeasures such as antioxidants, pharmaceuticals and gene therapy."

However, in this article we will consider issues relating to the possibility of being able to create some kind of "active shield". How can we borrow from nature's solution by taking a portable artificial, mini-magnetosphere along with the spacecraft? Figure 2 shows a magnetospheric bubble more of the dimensions of kilometres rather than multiples of Earth radii. This type of shield is not in competition with other approaches such as material barriers – it is likely that more than one layer of protection will be needed when human lives are at stake. It is also unrealistic to expect any quantity of shielding to be completely effective; the aim is to make the odds of surviving acceptable.

The magnetosphere reaches approximately 10 to 20 Earth radii (R_{E}) in the direction facing the Sun and can extend up to 1000 R_{E} in the shadow or magnetotail due to the drawing out effect of the flowing solar wind. The Moon's average orbital radius is 60 R_{E}, which means it goes in and out of the Earth's magnetosphere, although it has no magnetosphere of its own. Astronauts *en route* to the Moon have to consider flight paths that ensure only a limited exposure to the boundary region or the tail, making the most of the Earth's magnetosphere. The Apollo astronauts were lucky – Mike Lockwood discusses just how lucky on pages 6.11–17. They missed being exposed to any major solar proton events that would have lead to either short-term radiation sickness (no joke on a spacecraft) or even lethal radiation exposure.

The energetic particles from cosmic radiation, in particular protons and electrons from the Sun, possess a charge and are thus affected by magnetic fields. However, the interaction is not as simple as might be thought at first glance.

Solar-wind energetic particles constitute a quasi-neutral ionized state, or plasma. In a confusing historical quirk, plasma got its name from the translucent part of blood, even though the physics "plasma" has nothing to do with biology. Plasma is the fourth state of matter. If you heat a solid you get a liquid; if you heat a liquid you get a gas; if you heat a gas you get a plasma. When the energy input is enough to strip the atoms of their electrons, they produce a "collective" of free positive ions and electrons. All "empty" space, be it interplanetary, interstellar or intergalactic, has to contain plasma. It is just at very low density. Stars, nebulae and pretty much everything else out in the universe is also a plasma, with a bit of dust here and there, and the odd black hole, so it is pretty important stuff to understand.

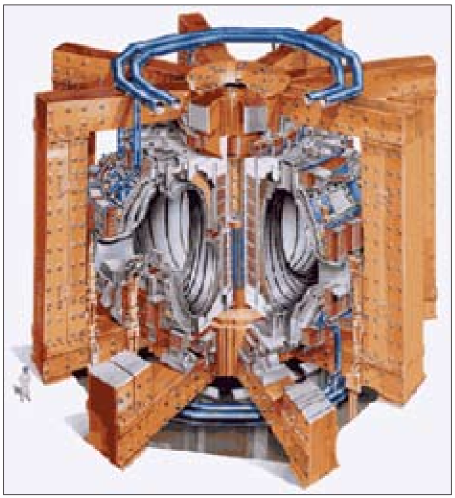
The defining characteristic of a plasma turns out to be its collective nature. What this means is, because of the linkage between the electric fields of the charges of the plasma, if you perturb one part of the plasma the whole of it can respond, a bit like slapping a jelly. Another defining characteristic of most plasma states is its truly "super" conductivity. There are exceptions, but most plasmas have virtually no electrical resistance. As a plasma consists of free positive and negative charges, if you try to inject an electric field, electrical current or magnetic field into a plasma it will very quickly set up currents and electric fields to try to keep the impinging fields outside. Plasmas really, really do not like to have electric fields or magnetic fields imposed upon them and they have the super high conductivity to back that up.

Magnetospheric plasma barrier

Here is where the importance of the Earth's magnetic field comes in. Empty space is filled with plasma of one density or another and so is Earth's magnetosphere. In fact it is critical to the action of the magnetosphere as a shield that the Earth's magnetic field does come with plasma.

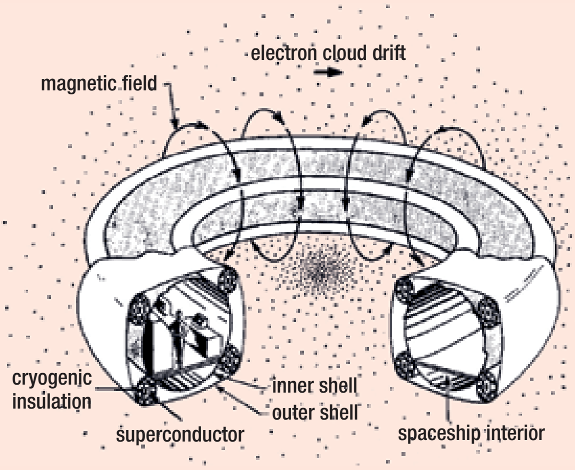
The solar wind consists of energetic particles racing out of the Sun in a fast flowing (say ~400 km/s) plasma. When this hazardous, high-speed plasma encounters Earth's dipole magnetic field, the solar-wind plasma "sees", from its perspective, a region of space with a different magnetic field and plasma density than it is carrying itself. It "sees" a magnetically confined plasma "wall" or barrier. The boundary region between the solar wind plasma and the magnetospheric plasma is the magnetopause, which consists of a turbulent interface and a shocked zone. The bow shock is sunward of the magnetopause because the solar-wind plasma flow is supersonic to the magnetospheric plasma.

The magnetospheric plasma really does not like having the solar wind plasma trying to push through it and so behaves collectively to keep it out. Fortunately for us, our magnetospheric plasma is well anchored to the Earth by our magnetic field and the Earth is heavy – so it is

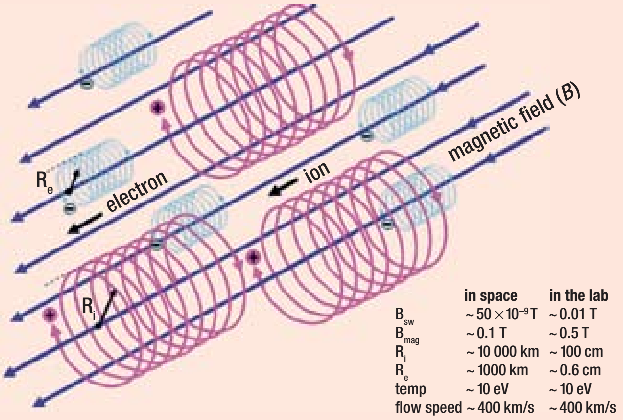


3: A schematic diagram of the world's largest tokamak, JET, the Joint European Torus at Harwell. Large magnetic coils around the vacuum vessel generate confining magnetic fields within and around the hot plasma. (EFDA-JET)

4: A possible approach to the design of a space vehicle incorporating a plasma shield. The magnetic field is provided by 4-turn superconducting coil. The currents in the coils could be tailored so as to cancel the magnetic field within the spacecraft, preventing hazards from fields to humans or instrumentation. (Taken from French and Levy 1967)



5: Larmor orbits and scaling between conditions in space and in the lab. Electrons and ions of a plasma rotate around a magnetic field. Electrons and ions have the same magnitude of charge but opposite senses so they rotate in opposite directions. The very much heavier mass of the ion means the radius of the orbit (Larmor radius) is very much larger than that of the electron.



	in space	in the lab
B_{sw}	~ 50×10^{-9} T	~ 0.01 T
B_{mag}	~ 0.1 T	~ 0.5 T
R_i	~ 10 000 km	~ 100 cm
R_e	~ 1000 km	~ 0.6 cm
temp	~ 10 eV	~ 10 eV
flow speed	~ 400 km/s	~ 400 km/s

not going anywhere. The solar-wind plasma is mostly forced to go around this obstacle, rather like a pebble in a stream (figure 1 again).

It is this interaction between the solar-wind plasma and the magnetosphere that works to keep some of the hazardous radiation in the plasma of solar energetic particles from reaching the Earth.

The importance of being a plasma

Is all you need to form a shield a magnetic field around an object, then? Well no, not exactly. But it helps. The description of the interaction gives the impression that the magnetic field is all that is needed to create a magnetosphere. This is, however, deceptive. The magnetic field is the starting point, maybe, but the "active ingredient" in the creation of a magnetospheric barrier is the plasma held at the barrier.

This may at first sound bizarre, but it is a necessary point to appreciate if an artificial magnetosphere is to be built as a shield to energetic particles. We want a man-made barrier with the minimum of power demands, because power generation is at a premium on any spacecraft. If we don't need to power excessive local magnetic fields close to the spacecraft, we're better off.

The magnetic field defines where the plasma barrier is and holds it in place. It does do some plasma capture or self-creates a plasma barrier, but knowing what the forces are that actually deflect the solar-wind plasma – and how to optimize them – dictates the practicalities of creating a shield. One of the reasons plasma physics is a tricky topic is such "chicken and egg" circular connections between magnetic, electric and charge concentrations. For instance, as charged particles of a plasma move around, perhaps due to a moving magnetic field, then the charges can generate local concentrations of positive or negative charge, which gives rise to electric fields. The motion of charges also accelerates currents and hence creates magnetic fields. These fields then affect the motion of other charged particles far away, as described in the box "How does it work?", p6.22.

Planets with no magnetic fields

Planetary bodies that do not have a magnetic field may not have magnetospheres quite like ours, but they can have a plasma barrier to solar-wind radiation that is reminiscent of a magnetospheric barrier – but not as effective at shielding the planet from the energetic particles because it is embedded in the planetary atmosphere. Venus is an example of a planet with a plasma barrier embedded in its atmosphere. Venus, like Mars and the Moon, has no dipole magnetic field extending out into space like Earth has. Venus's atmosphere is also very dense. Without the protective shield of a magnetosphere in space there is nothing to stop the solar-wind plasma from hitting the upper atmosphere at full force on the dayside face of the planet. Here a "plasma barrier" is formed without a magnetic field being there first. But because the magnetic field is not there to hold the plasma well above the denser parts of the planetary atmosphere, collisions between the actively created plasma from the solar radiation and solar wind and neutral gas particles of the atmosphere effectively quench the plasma by thermalizing it and exchanging electrons with the plasma ions to form atoms. There is not enough plasma there to act as an effective enough barrier to stop the most energetic particles reaching the Venus surface.

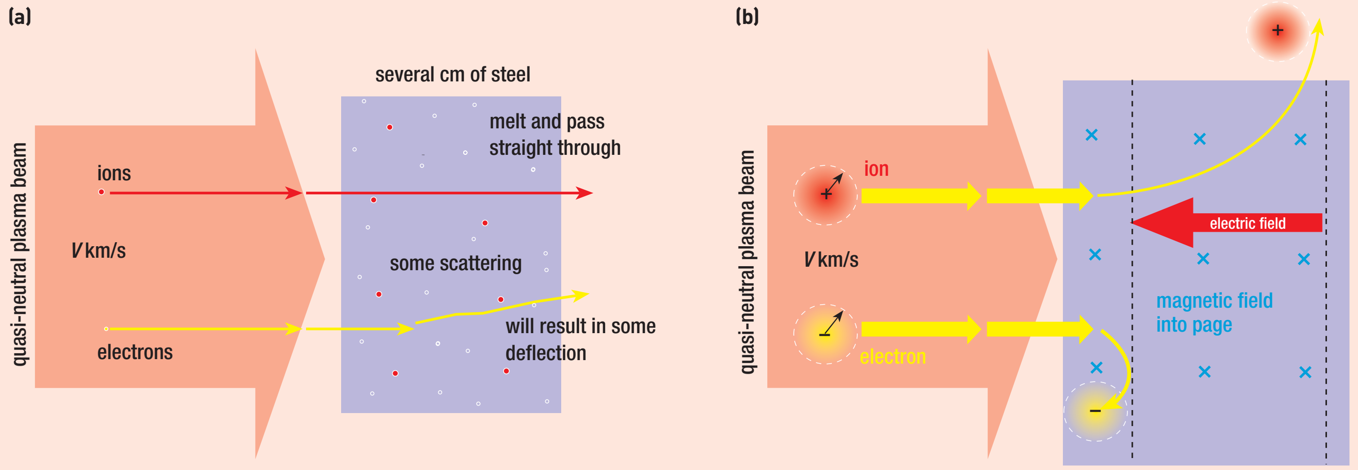
Does size matter?

Although we know that a barrier as large as the Earth's magnetosphere does shield the Earth from much of the solar-wind energetic particles, is the protection scaleable downwards to the size of a spacecraft? The answer is yes, we believe so. But to test this we need experiments on real plasmas in the laboratory, plus computer simulations.

The argument often given against astrophysics experiments in general is that these mammoth processes cannot be scaled down to fit in a laboratory. Everyone agrees that you cannot put the whole of the magnetosphere into a lab, but that is not necessarily what is needed. To look at the physics of a specific region, especially boundaries or aspects of auroral emissions, it is perfectly possible to investigate within and scale to the lab. As for understanding the environment of a magnetosphere as a whole around the Earth, that is a different question, essentially one of how all the parts fit together in nature.

When scaling the very diffuse, warm, low-magnetic-field plasma of space one has to scale not the linear dimensions but the dimensionless plasma parameters. What this actually means

POSSIBILITIES FOR MATERIAL AND MAGNETIC SHIELDS



6 (a): A metal or material shield. (b): A pure magnetic barrier – no plasma.

If you have a shield made of some solid material, say steel, it works by interaction with the plasma beam, but the speed of the solar-wind plasma means that this is not very effective. The solar-wind plasma (coming in from the left-hand side here) is a collection of very fast electrons and ions. Electrons and ions are small and their kinetic collision cross-section with the nuclei in a material barrier is very small, especially at high velocities (figure 7a). They tend to pass straight through or are slightly deflected unless the barrier is very thick, whereupon they can produce secondary radiation.

Early ideas of a barrier based on the magnetosphere considered aspects of it that we now know are interconnected. A pure magnetic-field barrier, with no plasma involved, is illustrated in figure 7b. The magnetic field gives directionality to the media. The opposite charges of ions and electrons makes them gyrate around magnetic field lines in opposite directions. So the presence of a magnetic field results in charge separation in space. This charge separation creates an electric field, which is what eventually stops the ions. When an electron encounters a region of higher magnetic field then it starts to gyrate around the magnetic field line. It does not matter which orientation the line is, somewhere on the Larmor orbit the particle is turned around. However, a magnetic barrier on its own needs to be a very strong field to achieve this without plasma.

is considering aspects such as the size of the particle orbits around the magnetic field lines, resonant plasma frequency, MACH numbers, illustrated in figure 5. Given that you cannot scale everything in the lab exactly, the method is to ensure that you scale what is important to the question at hand. In this case, summarized in figure 5, this is the boundary region of one plasma impacting another.

The important parameter for scaling mini-magnetosphere interaction is that the *electron* orbit around the field lines (the electron Larmor orbit) is smaller than the barrier in the experiment. In the past it was believed that the mini-magnetosphere had to be very much larger, so that the mini-magnetosphere was much larger than the *ion* Larmor orbit (figure 5). This very much larger shield would be prohibitively power-hungry to support and would produce excessive fields on-board the spacecraft. These earlier models treated the plasma like liquid mercury with a magnetic field frozen in it. Physics understanding has moved on thanks to better computer simulations that do not have to be limited to the fluid-like behaviour of a plasma. Computing capabilities have only just allowed the kinetics of the separate constituents to be, at least in part, simulated. However, it is still easier to use an actual plasma to be its own analogue computer. A real plasma doesn't need to think about how to behave, so combining plasma experiments with computer simulations means that the physics can be checked.

Shields up, Scotty!

The idea of an artificial, or more properly, an "active shield" around a spacecraft is familiar in the form of "deflector shields" from science fiction, such as *Star Trek*. An active shield is created – probably by Scotty down in engineering pressing a button – so that an invisible shield suddenly extends around the Enterprise, protecting against ion storms or Klingon particle beams (both of which sound like plasmas). The similarities are no coincidence of course – the creators of shows like *Star Trek* try to keep as scientifically honest as plot devices and TV budgets allow. It is more than likely that they borrowed the idea of a shield from the Earth's magnetosphere in the first place – they just didn't bother about actually building one.

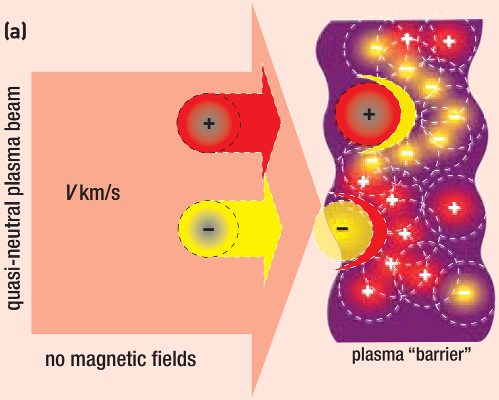
Serious scientific consideration of building active deflector shields is not new. In the 1960s there were several suggestions for active shield technology, in the following general categories: pure electrostatic field, pure magnetic field or pure plasma shields. Roughly speaking they are all variations on a theme – that of trying to use some of the shielding characteristics of a magnetosphere in miniature around a spacecraft. However, each approach had major drawbacks, most commonly the requirement for massive power generation to create an effective enough shield to keep the solar wind away from the spacecraft. Another prohibitive aspect was the need for very large electric or magnetic fields within the spacecraft in order to allow for the $1/rn$ diminution of the shield into space. And very high fields close to electronics or people can bring other problems.

However, the major omission in the analysis was the assumption that these forces can be separated. In the plasma environment, they are too interdependent. Wherever there is a plasma there are magnetic fields, wherever there are interactions of plasmas of different densities and temperatures there are going to be electric fields locally. So each one of these proposed active shield approaches thought to be distinct in fact incorporate all the others intentionally or not.

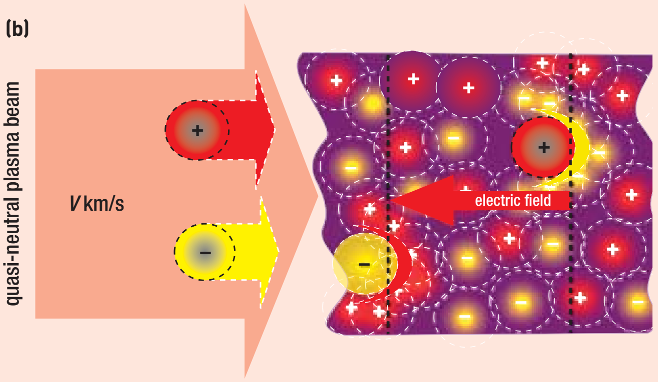
With all the forces working together, the power and near-field issues are not as significant as thought in the 1960s. There have also been significant improvements in our understanding of how plasmas behave and how to confine and control plasmas, largely thanks to the extensive pursuit of controlled thermonuclear fusion.

The knowledge of physics and engineering that has been acquired from magnetically confined fusion work is of specific relevance to mini-magnetospheres. In this an artificial, highly energetic plasma of up to MeV energies is created inside a vacuum vessel generally

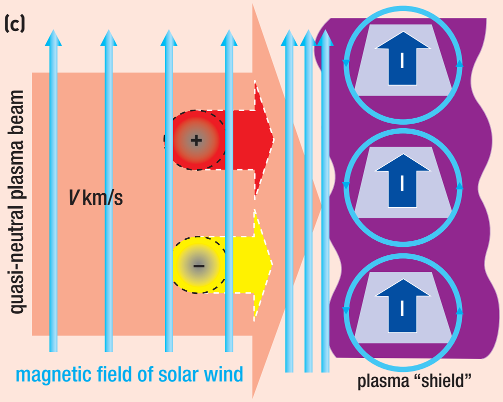
HOW DOES IT WORK? THE PHYSICS BEHIND THE MINI-MAGNETOSPHERE PLASMA BARRIER



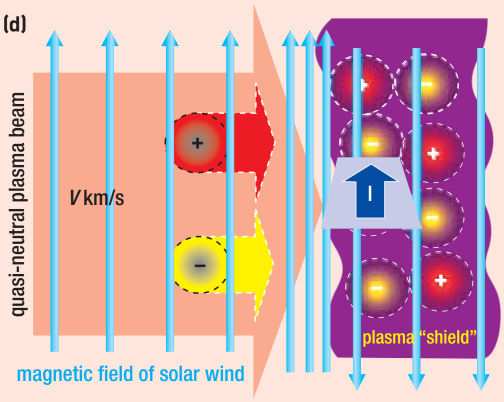
7 (a): A plasma impacting a plasma.



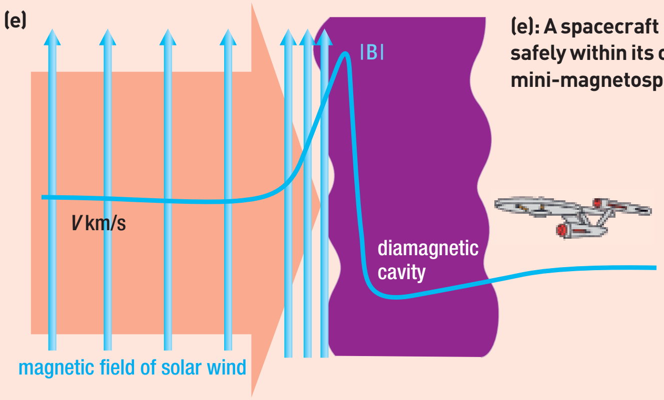
(b): A plasma impacting a higher density plasma barrier.



(c): A magnetized plasma impacting a plasma barrier.



(d): A magnetized plasma impacting another higher density magnetized plasma.



(e): A spacecraft safely within its own mini-magnetosphere.

It's a question of cross sections. Imagine an overall neutral solar-wind plasma beam consisting of equal numbers of energetic ions and electrons impacting a plasma barrier one million times less dense than air. There are no magnetic fields involved.

Unlike the kinetic cross-section interaction in the case of the material barrier, the electrostatic field of charged particles is much larger than their physical dimensions. Thus if the solar-wind plasma is impacting a barrier made of similar electrostatic charges, the interaction cross-section is considerably higher (figure 8a).

If the barrier plasma is higher density (figure 8b), what happens when the ions and electrons try to enter the barrier? Plasma has very high conductivity. The ions and electrons are not held together, after all, in a solid lattice like in a good conductor such as copper wire. Plasmas behave *collectively* by nature and only relatively small adjustments by *many* individual particles act to cancel the impinging electric field caused by a foreign charged particle from the solar wind. However, the energetic ions and electrons of the impacting solar-wind plasma have the same charge but very different masses.

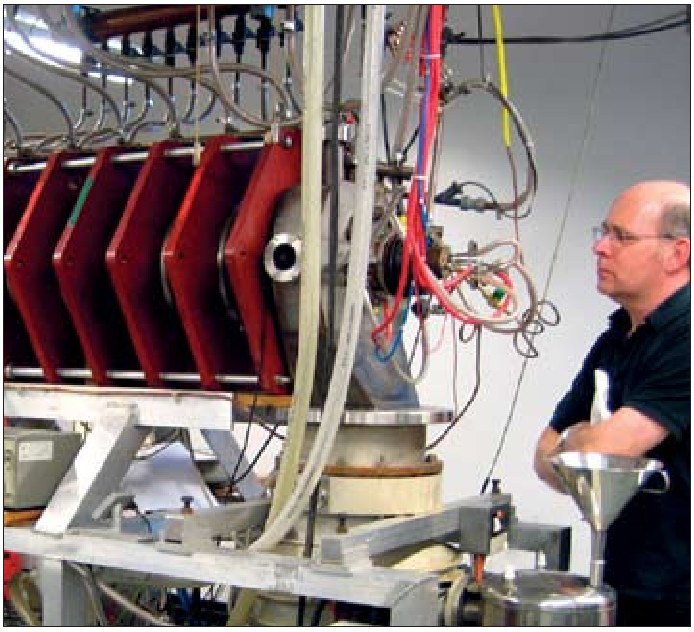
The electrons, being so light, are stopped very quickly by the collective adjustments of the barrier plasma trying to keep out the intruding electric fields. The ions carry on deeper into the barrier plasma because of their greater inertia. The ions are finally stopped by the electric field created by charge separation when they realize they have left their electrons behind. None of this action actually *requires* a magnetic field to be present.

When the magnetic fields are added to the solar-wind plasma, as in figure 8c, there's a bit of a pile-up at the barrier. The Sun itself is essentially a big knotted tangle of plasma, producing lots of magnetic fields. When parts of the Sun's plasma are thrown into space to form the solar wind, this magnetic field is still embedded in it and forms the Interplanetary Magnetic Field (IMF).

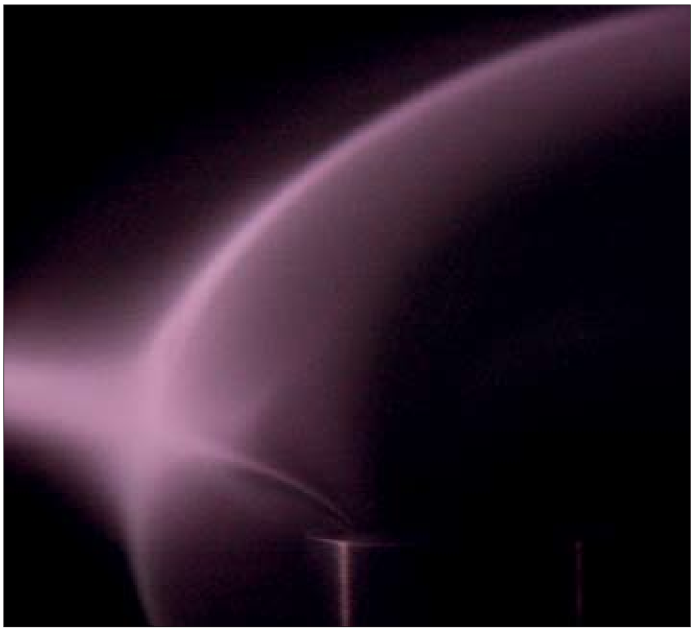
Lenz's Law means when the magnetic field embedded in the solar wind encounters a higher density plasma barrier, it tends to "bunch-up" at the interface. This is caused by "mirror-image" currents (into the page in figure 8c) that form within the plasma barrier acting, once again, to keep out the impinging magnetic field from entering the highly conducting medium. The currents in the plasma are such that the magnetic field on the solar-wind side is enough to cancel out the solar-wind magnetic field.

Surprisingly, to the first approximation the magnetic field of the barrier is not necessary to create the barrier. A Perspex box with a plasma in it would do, in principle. The magnetic field of the shield is primarily there to *confine* and *control* the plasma of the barrier, in this situation of creating an artificial magnetosphere. This statement appears contradicted by the facts, but a plasma encountering a stationary magnetic field on its own can create a plasma – it just takes a lot more power than if a plasma is in the barrier in the first place.

Putting all the forces together creates a cavity within the flow of the solar wind within which the spacecraft and its inhabitants can reside relatively safely (figure 8e).



8: The solar wind in a bottle. The linear device that produces the laboratory "solar wind" magnetized beam, with John Bradford of the RAL team.



9: A mini-magnetosphere in the lab, with the "solar wind" plasma flowing from left to right. The crescent of light marks the mini-magnetopause.

shaped like a doughnut or torus vessel (figure 3). The aim is to get the positively charged hydrogen ions close enough together for long enough that the nuclei can fuse and, in doing so, release energy. The difficulty is the temperatures that the ions, and therefore the plasma, has to reach: if the plasma touches any material such as the steel of the vacuum vessel wall, the reaction is quenched and the plasma instantly extinguished. This is a fail-safe in a nuclear reactor, but makes fusion hard to achieve. In a torus, the plasma is held away from any walls or materials by magnetic fields that loop around and around. It was envisaged back in 1967 that a spacecraft with a magnetosphere-type shield might be a torus shape too (see figure 4), like an inside-out tokamak. The people are inside the air-tight "vacuum vessel" and the plasma of the solar wind is on the outside. The action of a tokamak is to keep a much hotter plasma (about 100 million degrees Kelvin), denser than the plasma in space by more than 10 orders of magnitude, away from a vacuum vessel wall – essentially at room temperature – and only 4 cm away, using only magnetic fields. These demands are many orders of magnitude more than is needed in space.

A mini-magnetosphere in action

With the connection between the likely technology for producing a mini-magnetosphere and the technology of magnetically confined fusion, it is hardly surprising to think that maybe laboratory experiments already in existence for fusion work could be used to study the physics behind mini-magnetospheres.

This has been done. A set of initial experiments to demonstrate "proof of principle" have been conducted by a team led by members of the Rutherford Appleton Laboratory in Oxfordshire, including groups from the University of York, Instituto Superior Técnico, Portugal, Umea University in Kiruna, Sweden and tokamak specialists from JET/EFDA at Culham in Oxfordshire. Figure 8 shows a photograph of the experimental equipment at the University of Manchester: a vacuum pipe, with magnetic field coils around it, producing an axially aligned confining magnetic field. The model solar-wind plasma flows continuously in a beam along the length of the pipe. At the far end it enters a target chamber where cameras and plasma probes detect how the plasma behaves.

In figure 9 the hydrogen beam is impacting, or rather not impacting, a high-field permanent magnet of 0.5 T. In the lab the magnetic fields have to be so high to make the orbits of the plasma particles small. In space, the equivalent field is only 50 nT, seven orders of magnitude less, so the field strength could also be lower. In the photograph the solar-wind plasma is coming in from the left-hand side and the cylindrical magnet is at the lower centre of the picture. The magnetic axis is pointing up the middle of the magnet with the south pole uppermost. The picture shows that the plasma has been deflected from the magnet. There is none within the cavity, except for the little bright field-aligned "auroral" link current structure that joins the "cusp" region to the magnetic pole of the magnet.

Captain's log, stardate –316748.85

Over the past 40 years, important progress has been made towards understanding and forecasting proton events. Irrespective of any manned space programme, effective "space weather" prediction is necessary to better protect vulnerable satellite and terrestrial systems. But at the moment, we still cannot reliably warn of these events except on timescales of a few minutes for people out in space. We need a protection system that can be deployed rapidly.

A major goal of the space agencies is to establish long-term bases on the Moon and then travel on to Mars. With flight times of 18 months to Mars and back, these astronauts are guaranteed to have a significant solar proton event.

As to the question of whether an active shield such as a mini-magnetosphere on a spacecraft is feasible in the engineering sense, here we can look to the technology being developed in parallel by the magnetic confinement fusion community and say yes, probably, especially given the lower field and power requirements needed in space. It is likely that superconducting coil technology will be more practical, too, by the time a shield for a real spacecraft is needed.

Recent computer simulations help and have confirmed what we think is the physics of the magnetospheric boundary outlined in this article. Laboratory experiments on plasmas also seem to confirm that our computer model is accurate. Finally, in space there is the AMPTE artificial comet experiments done in space in the solar wind in the 1980s that demonstrate that the physics translates to the smaller scale.

To protect the brave men and women who will boldly go into space, is going to take every approach in our armoury. But please remember, as Dr McCoy might say: "We are scientists, not miracle workers." ●

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