Can artificial miniature magnetospheres be used to protect spacecraft?

Article · September 2017

Ruth A. Bamford
Science and Technology Facilities Council

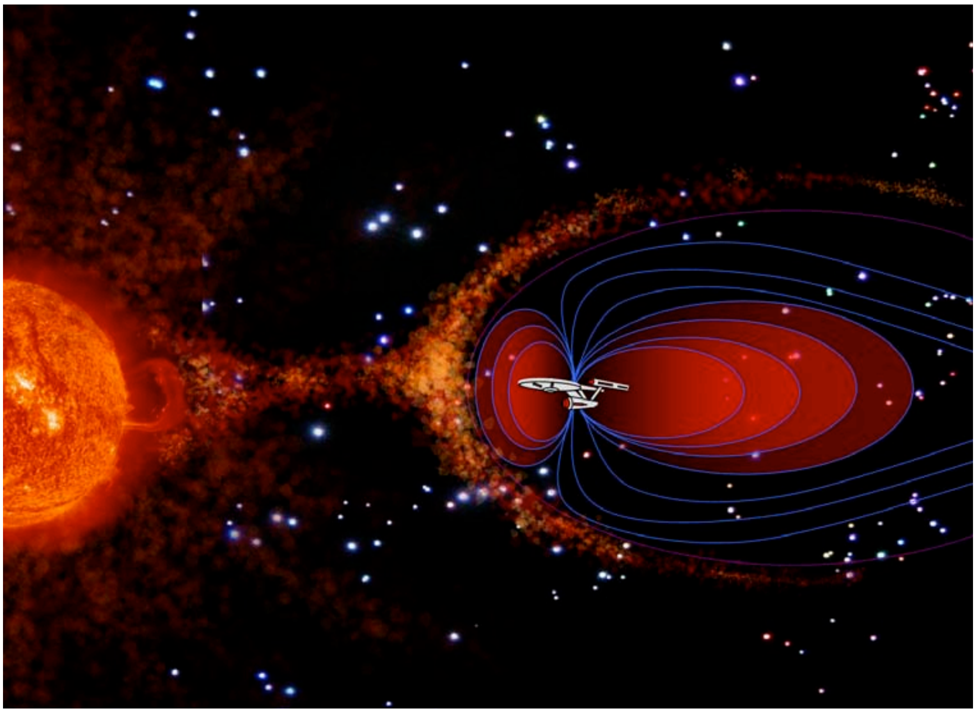
Journal of the British Interplanetary Society, Vol. 70, pp.344-352, 2017

CAN ARTIFICIAL MINIATURE MAGNETOSPHERES BE USED TO PROTECT SPACECRAFT?

RUTH BAMFORD, Rutherford Appleton Laboratory, Harwell Innovation Campus, Chilton, Didcot, OX11 0QX, UK
Email: Ruth.Bamford@stfc.ac.uk

Spacecraft in interplanetary space and the radiation belts are vulnerable to `cosmic rays'. Solar storms produce large numbers of energetic ions and electrons that can penetrate and disrupt solar panels, electronics and human tissue. For decades, ideas have been considered as to how to use electromagnetic fields to deflect hazardous energetic charged particles from the vicinity of the spacecraft, so as to prevent them from ever impacting. The conclusion has always been that too much power is needed to implement active shielding with current technology. Until recently nobody has reexamined how the particles interact with the magnetic or electric field. The interaction is assumed to be via straightforward vacuum single particle dynamics, in which electric fields slow down/speed up charged particles and magnetic fields bend their trajectories around field lines. However, laboratory experiments and analyses of objects in space have shown that things are not that simple. Here we reexamine the principles using computer simulations, laboratory experiments and analysis of natural mini-magnetospheres on the Moon, which are now recognized as shielding the lunar surface from the weathering effect of eons of solar wind proton bombardment..

Keywords: Radiation Protection, Active Shielding, Solar Storms, Mini-Magnetospheres



RUTH BAMFORD (STARSHIP ENTERPRISE COURTESY OF PARAMOUNT/CBS)

Fig. 1: The concept of "active", or electromagnetic, shielding for spacecraft in science fiction undoubtedly comes from the confirmation of the existence of the Earth's own deflector shield, the magnetosphere, in the late 1950s, by the Explorer series of spacecraft.

INTRODUCTION

If mankind is to explore the solar system beyond the confines of our Earth and Moon the problem of radiation protection must be addressed. Galactic cosmic rays and highly variable energetic solar particles (solar cosmic rays) are an ever-present hazard in interplanetary space. The same is true for unmanned satellites in and around the Earth's radiation belts. The energy of the "killer" particles may be less, but so is the threshold of vulnerability of solar cells and electronics.

Of greatest concern are the deep penetrating ions: protons for their large numbers and broad spectrum, and high Z ions due to their charge per unit mass. Because these particles have an electrical charge, this suggests the potential to use "active" or electromagnetic forces as a shielding mechanism. As technology has advanced since the 1950s, when it was first demonstrated by in-situ measurements that the Earth's, relatively weak magnetic field was acting as a deflector shield, many engineering schemes have been proposed for the generation of a pure electric or magnetic field on board a spacecraft in order to achieve this. At the boundary where the Earth's magnetosphere holds off the worst of the solar wind, the magnetic field strength is about 100 nT and it is observed that electric fields form (Bale 2003).

However, in many of the suggested operational schemes to artificially create a miniature magnetosphere or other active shield about a spacecraft, little attention was paid to how the incoming charged particles were deflected or reflected. Generally the interaction was presumed to be via simple single charged particle dynamics in a vacuum where the charged particles are either slowed down or accelerated by electric fields or bent around magnetic field lines (Larmor orbit). However the truth is far from that. Although very diffuse, interplanetary space is a conductor. The solar wind consists of equal numbers of positive ions and negative electrons, forming a plasma. It is the high energy tail of this charged particle distribution that constitutes the hazard to men and machines. The number of particles in interplanetary space or in the radiation belts, is generally of the order of 5 to 10 ions and electrons in 1 cm^{-3} (approximately the volume of the end of your thumb). Although energetic, the charged particles are unlikely to collide with each other ballistically and are therefore "collisionless". They only interact by their electric and (through collective motion) magnetic fields. This is a defining characteristic of plasmas, especially ballistically collisionless plasmas in space. Electric forces are 10^{39} times more powerful between charges than gravity. Mass motions (i.e. currents) in the plasma, even at some considerable distance, influence charged particle motion via the long range effect of magnetic fields.

More recently, analysis accounting for the plasma environment has been conducted. The models used to analyse the interaction of a magnetic or electric obstacle placed in a flowing plasma, similar to that of interplanetary space or radiation belts, have, however, generally been guided by models of planetary magnetospheres. These computer models follow a theoretical approach which assumes a magnetised fluid analogy to describe the plasma behaviour (magnetohydrodynamics or MHD). No electric fields are allowed in MHD except those currents that are added manually (Hall terms). No charge separation between ions and electrons is allowed, because the required scale size for MHD to be appropriate is too large to identify any kinetic effects, or to reveal the particle nature of the plasma.

Because MHD is designed for the scale size of a large planet, when applied to a small human scale of spacecraft the solutions come out very large. MHD fluid model cannot resolve smaller scale processes, it cannot determine whether or not a shield could function at sizes below the model resolution. As a consequence, it is concluded that a magnetospheric cavity can only work if it is larger than ~100 km. Such a large artificial magnetosphere would require an impractical level of power on board the spacecraft to achieve 100nT, 100km away from the source. For practical power levels, the range over which the electromagnetic forces are extended from a single spacecraft would have to be more modest like a kilometer or less.

The effectiveness of a "mini-magnetosphere" acting as a radiation protection shield therefore needs to be reconsidered and not simply dismissed, based on outdated assumptions and a fear of overlap with science fiction. Here we explicitly include the plasma physics necessary to account for the solar wind and its induced effects. It is revealed as very complicated. We show that, by capturing/containing this plasma, we can enhance the effectiveness of the shield. Evidence to support these conclusions is shown from studying (1) naturally occurring "mini-magnetospheres" on the Moon, (2) computer simulations and (3) laboratory experiments using a Plasma Solar Wind Tunnel.

The focus here is on the physics, not the engineering. However some guiding principles and estimates, as well as some indications of developing technologies in superconductivity, will be included.

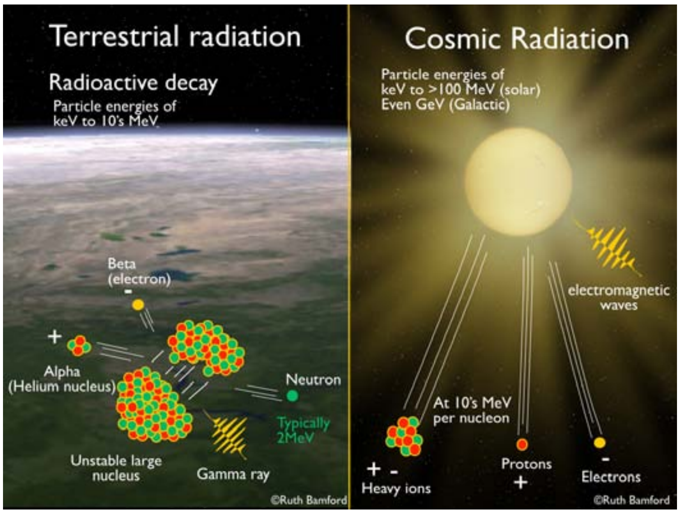


Fig. 2: Cosmic rays in space are a different type of radiation than that encountered by radiation workers. On Earth radiation hazards (left) are generally related to radioactive decay of heavy elements like radium, uranium and plutonium and electromagnetic waves like gamma and x-rays. The radiation in space has a broadband electromagnetic component but also has an additional form of radiation not seen on Earth except in particle accelerators and as cosmic rays. Extreme forces in the centres of galaxies and supernova explosions can accelerate protons, alpha particles, and heavy nuclei, such as iron, to energies from MeV to 100's of GeV. At these energies, the particles are predominantly the nuclei of atoms and electrons separately, constituting a high-energy plasma.

THE NATURE OF THE PROBLEM

The greatest threat from radiation in space lies in its uncertainty. The radiation of cosmic rays is different from what we are familiar with on Earth (see Fig. 2). Excluding the electromagnetic spectrum, the greatest radiation concern in the space environment arises from energetic charged particles and neutrons. Primarily this is due to their inertia, meaning that they are hard to shield against materially, and their electrical charge (where appropriate) disrupting the bonds and structures of solids and liquids as they pass through. Neutrons are short lived and decay into a proton and an electron (plus neutrino) in about 9 minutes. Co-incidentally the Earth is approximately 8 light minutes away from the Sun. So solar neutrons are not a problem, however neutrons are a common spallation product of energetic ions impacting the upper atmosphere and materials such as spacecraft walls or cladding. Ironically this can mean the radiation environment inside a spacecraft, like the ISS, can be worse than on the outside, depending upon the energy spectrum of the incoming particles, the materials used and the fragment spectrum and vulnerability. One way to avoid the neutron problem is to prevent the particles from ever reaching the spacecraft hull by using an active shield.

The main sources of high speed/energetic ions and electrons in space are: (a) Galactic cosmic rays (GCR) which have GeV energies but constitute only approximately 1 part in a million of the overall cosmic rays. (2) Solar energetic particles that consist of a continuous but varying solar wind interspersed with large eruptions. (3) The radiation belts (Van Allen belts) around the Earth that can damage spacecraft in transit and in orbits that intersect them.

Solar "storms" come in various categories : (1) events such as coronal mass ejections (CMEs) that are large in number density of particles, but slow to arrive at Earth. These result in some energetic particle penetration but mostly affect the radiation belts some days later, by filling them with additional higher energy ions and electrons. (2) Flares and non-Earth directed CMEs that produce unexpected solar particle events (SPEs) (through shock waves near the sun). These particles are very energetic and arrive at Earth within minutes without warning.

In summary, the events of greatest concern are the short-term solar eruptions of energetic high Z ions and protons, and so called "killer" [to instrumentation] particles in the radiation belts. For manned missions in interplanetary space, GCR exposure during a long term mission is of particular concern and dosage levels may be highly variable.

Fig. 3 provides an indication of the effectiveness of material shielding against a solar particle event. It shows that for a manned mission on the Moon, where crew survival is mission critical and resources greater, a reasonable material cladding can mitigate most of the impact of a solar particle event (Nelson 2016). But this is a gamble. The Curiosity mission showed that the radiation received going to Mars was much higher than anticipated. It is not clear what effect very extreme events would have on full body dose or on all the spacecraft systems. Nor are the effects of long term exposure and material activation/ thermalisation caused by cosmic ray impacts on the shielding well understood. This latter issue has become a matter of debate even for astronauts in low Earth orbit (Delp 2016).

An additional shielding resource that would reduce the uncertainties and material activation would be preferable, as long as the power, mass burden and effectiveness warranted it.

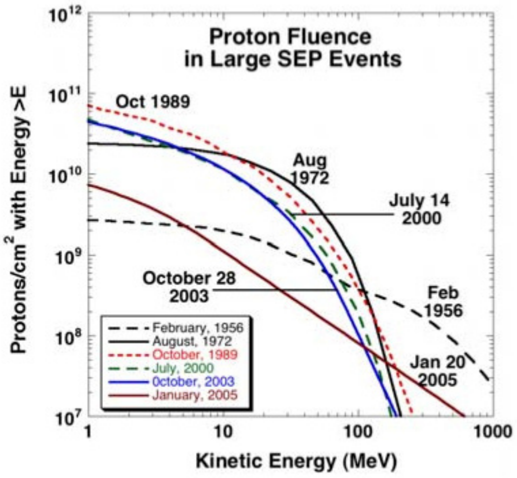


Fig. 3: The integral fluence spectra (sum of all fluence below a given energy value) measured at 1 A.U. for a several large SPE events. The arrows indicate ranges in aluminium for protons of energy 30 MeV/n (penetrate a space suit) and 60 MeV/n (penetrate spacecraft hull). For these events, total fluence for energies >30 MeV ranged from $2x10^8$ to $8x10^9$. (From Nelson 2016, after Wilson 1997.)

ACTIVE SHIELDING

"Active" shielding of spacecraft occurs ubiquitously in science fiction. It refers to the use of any electromagnetic force to screen, protect or shield a spacecraft or satellite. The origin of much of this fictional use is the awareness of the Earth's magnetic field creating the magnetosphere, which deflects, reflects and slows a sufficient amount of the incoming energetic particles and cosmic rays to ensure that life on Earth continues. The idea of creating a small, transportable, artificial or mini-magnetosphere onboard a spacecraft is elegant, and therefore very appealing. As has already been explained in the introduction, practical implementation of active shielding has always anticipated a vastly unrealistic power requirement. This has been the case for both magnetic field generated and electric field generated concepts. Often the electric field generated schemes claim to be power free, based on the incorrect perception that the artificial repelling electric field from a spacecraft would remain indefinitely. However, no matter what the geometry, space plasmas will be attracted to such an electrostatic anomaly, forming charge sheaths that would cancel the electric field. Thus trying to artificially maintain an electrostatic bubble against this "short circuiting" behaviour of the charge carriers of the solar wind will demand continuous power.

HOW THE ENERGETIC CHARGED PARTICLES ARE DEFLECTED

The shielding arises from artificial manipulation of the collective electromagnetic properties of a plasma. A more accurate name for the shield would be a plasmoid, rather than a mini-magnetosphere. The name "mini-magnetosphere" comes from the discovery of crustal magnetic anomalies on the Moon, shielding its surface. This will be discussed later.

How plasma physical processes shield a region surrounding a spacecraft is illustrated in the series of images in Fig. 4.

The following sections show the validation of the principle

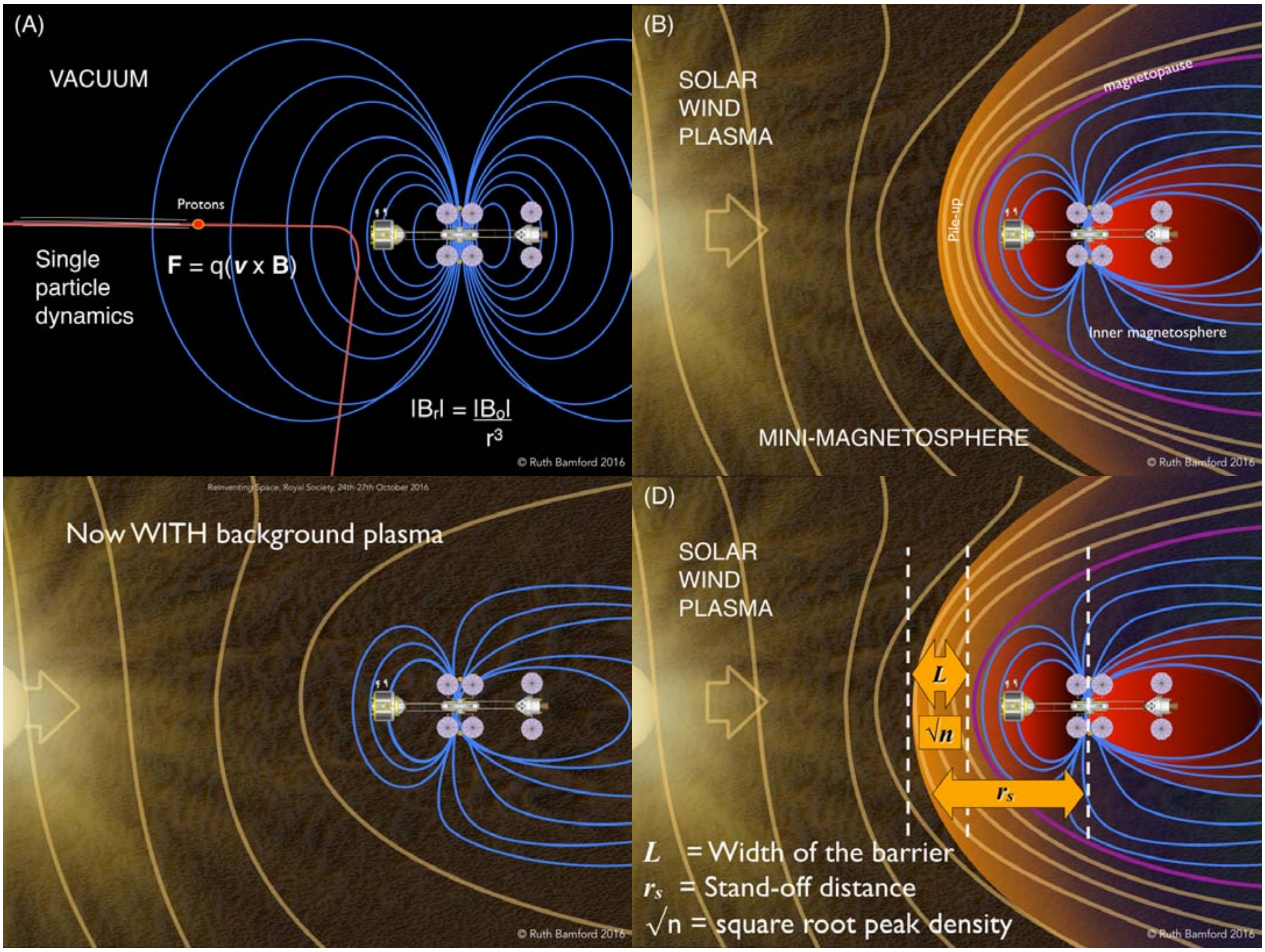


Fig. 4: How it works.

(A) Single particle dynamics prediction for how a highly penetrative energetic proton bends its trajectory when it encounters a magnetic field in vacuum. This assumes that the positive and negative charged particles of the plasma environment from the solar wind have no effect on the incoming particle.

(B) When we add the effect of the solar wind plasma, the symmetric dipole magnetic field in vacuum is distorted by the plasma pressure of the solar wind. Density and field pile up at the boundary until a balance is reached.

(C) If the abrupt change in gradients is of the order, or shorter than, the natural bending radius of the heavy protons, then the protons can overshoot, creating a charge separation electric field, pointing in the direction needed to preserve neutrality. This will remain for as long as the gradients are sustained against dispersal. Electric fields are 108 times more effective in changing the velocity of particles than magnetic fields. It is, therefore, the electric field that does the majority of the slowing down and deflecting of the proton distribution. Rogue extreme energy ions will also experience "a kick" from the electric field generated by the general population. The extent of their exclusion from the interior depends on their initial trajectory and the magnitude of the electric field, which is proportional to the square-root of the pile-up plasma density and the steepness of the gradient. Neither of these parameters necessarily directly require large artificial magnetic fields, as was supposed in the past. The artificial magnetic field is there to provide control and prevent diffusion and dispersion of the plasma barrier.

(D) The stand-off distance r_s and the barrier with L and the plasma density $\propto \sqrt{n}$ are key parameters for determining the shield effectiveness.

outlined in Fig. 4, by the use of particle-in-cell (PIC) code computer simulations, laboratory experiments and analysis of natural mini-magnetospheres on the Moon side-by-side with computer simulations.

VALIDATION IN A LABORATORY SOLAR WIND TUNNEL

Just as the aerodynamics of a full size aircraft can be analysed in miniature in the laboratory by the careful use of dimensionless parameterisation, so can the interaction of active shielding be modelled in an appropriately dimensionlessly scaled Plasma Solar Wind Tunnel (Fig. 5 overleaf).

This showed that the protons were deflected much more efficiently than a vacuum calculation of magnetic bending or plasma MHD fluid modelling would have suggested. For further details see Bamford 2007 and Gargate 2008.

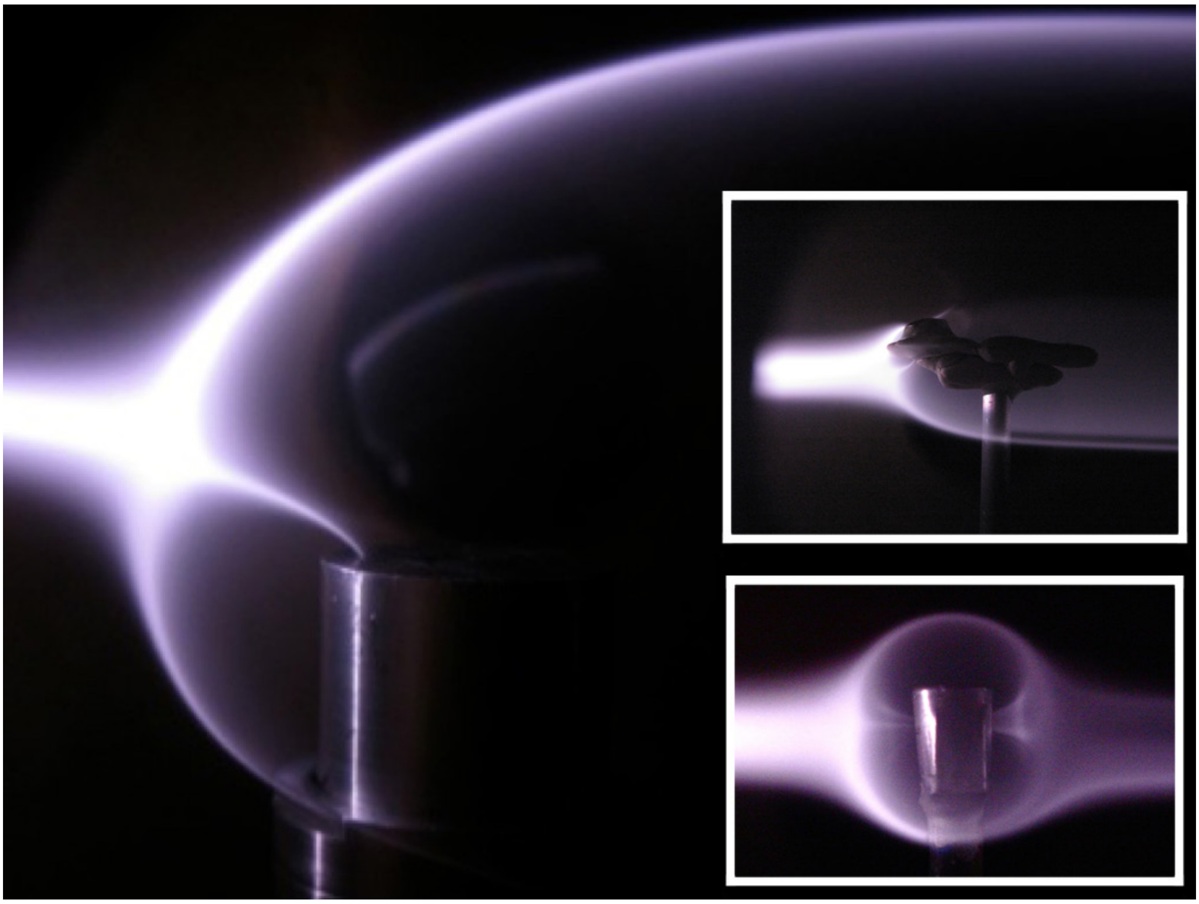


Fig. 5: Photographs of a "mini-magnetospheres" in a laboratory Plasma Solar Wind Tunnel. The main image shows the glowing, supersonic, collisionless proton plasma flowing from left to right, encountering an approximately 25mm diameter 0.2T magnet axis pointing upwards. The filament going into the top of the magnet is a field-aligned current, as happens in the Earth's auroral regions. This can be seen more clearly in the lower inset image, where a 10mm magnet of similar field strength is aligned, with its axis parallel to the incoming plasma flow. Here the auroral ovals at both the north and south poles of the magnet can be clearly seen. The upper inset shows a test "craft" using a smaller magnet in the Solar Wind Tunnel. In every case, the result is a narrow deflector barrier and a proton free cavity with, depending upon orientation, a magnetospheric wake. Quantified validation of the forces and densities was determined using probes. (Bamford 2007.)

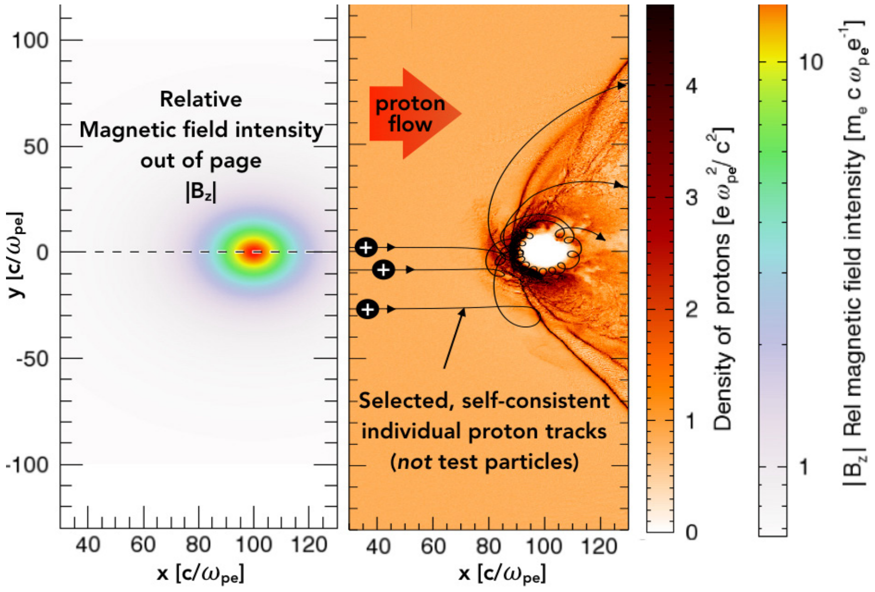


Fig. 6: A 2D PIC code simulation of a energetic plasma flow ($v_{sw} = 0.2c$ and $M_A = 2$) impacting a magnetic obstacle. The black lines represent ion trajectories and illustrate the typical Larmor radius scale after the particles are reflected. The units are all in dimensionless plasma units that scale with plasma density. For a plasma density of 10cm^{-3}, 1 distance unit [c/w$_{pe}$] ~1 km, the peak magnetic field here would be ~0.1T. (Adapted from F. Cruz MSc Thesis, IST Lisbon, 2015.)

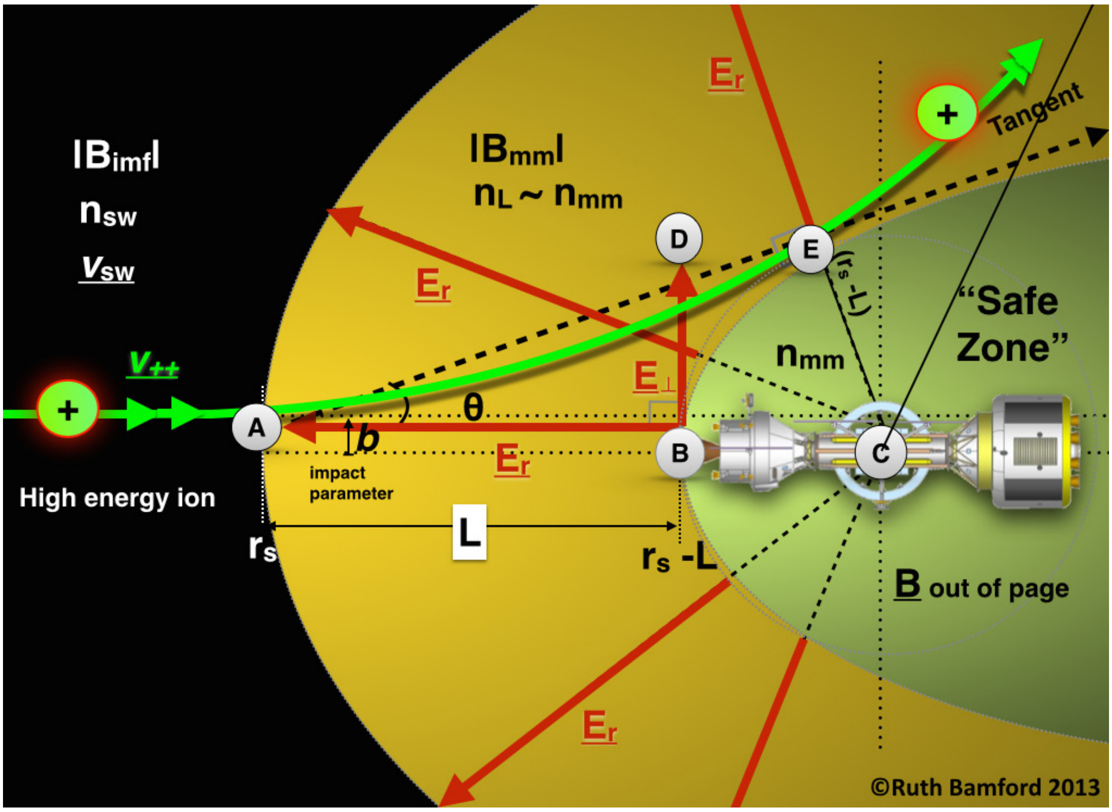


Fig. 8: Mini-magnetospheres were first identified on the Moon (Lin 1998). Unlike the Earth, the Moon has no overall magnetic field. It does, however, have patches of crustal magnetic fields. The surface magnitude of these fields is approximately 1/1000th that of the Earth's magnetic field at sea level. Nevertheless, magnetic cavities and other signatures of magnetospheres have been detected by surveying spacecraft.

The main photograph shows the simulated solar wind plasma (glow) encountering a 0.3T magnet. Rather than impacting the magnet the supersonic, collisionless hydrogen plasma flow is abruptly deflected into a narrow sheath (which can be seen to be 3D in alternative views). The flowing ions have a radius of curvature (the Larmor radius arising from the intensity of magnetic field present in the solar wind tunnel) which is larger than the overall dimensions of the photograph. However, rather than the ions spiralling out from the boundary, they can be seen to be channeled by a narrow (and intense) electric field until they are past the obstacle. The narrowness of the barrier illustrates both the existence of the electric field discussed in Fig. 4 and its dominance in controlling the ions.

COMPUTER SIMULATIONS

A particle-in-cell (PIC) computer simulation of a supersonically flowing plasma (left) is shown in Fig. 6. The initial setup of the 2D simulations has the dipole aligned along z. The plasma is continuously injected from the left boundary and flows along the x direction. Part of the plasma is initialized inside the box (indicated in grey), to reduce the computation effort. The colour map indicates the dipole field strength, normalized to its maximum value, determined by a cutoff introduced in the dipolar field (right). The plasma flow (orange) with v = 60,000 km/s and Alfven Mach no. = 2, interacts with a magnetic dipole. The black lines represent ion loci from selected ions that are a self-consistent part of the simulation outcome. They show the typical Larmor radius scale and the abrupt changes in direction caused by the electric field at the barrier. Some of the deflection is due to the effects of reducing Larmor orbit, when approaching a more intense magnetic field. However, many of the ions make abrupt changes in direction due to the charge separation electric field.

VALIDATION IN SPACE

Naturally occurring mini-magnetospheres on the Moon (described in Fig. 5) offer an opportunity to quantifiably validate the principles of mini-magnetospheres as shielding from cosmic rays. The multitude of international lunar survey missions provide a comprehensive database of in-situ, full scale observations to compare with theory.

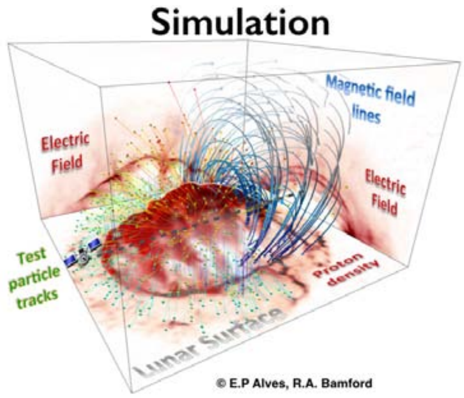
The main image in Fig. 8 shows a 3D fully self-consistent, PIC simulation of a mini-magnetosphere deflector shield occurring on the Moon. The simulated magnetic anomaly consists of a dipole whose magnetic axis is parallel to the surface but buried below it. Being 3D it shows how the outwardly pointing, narrow electrostatic field forms in every orientation resulting in a protective `dome' that scatters the incoming protons, thereby reducing the proton flux reaching the lunar surface. The dome is compressed by the solar wind pressure, resulting in a spreading of the dipole mid-plane, parallel to the surface magnetic field lines. At the edges of the dome, the narrow, electrostatic sheath intersected the lunar surface, channeling a high proportion of the impacting proton flux into narrow regions or `lanes' around the edge of the protected dome. The width of these enhanced proton outlines are of the order of the electron dynamical effects (kilometre or less) and look in form and width very similar to the "dark lanes" of the lunar swirls. Similar electron scale plasma filamentations occurred at the poles, oriented horizontally in the 3D example used here.

Taken together, the observations and simulations provide support for the hypothesis that the spectral effects observed in the lunar swirls are due to differential proton bombardment. One prediction of this work is that the widths of the dark lanes will be the same for any of the lunar swirls distributed about the Moon, whether they are in either large conglomerations or isolated patches.

Confirmation that Mini-magnetospheres can shield regions of space from high energy solar protons is found by in-situ measurements made by spacecraft flying through the “bubbles” shown in Figs. 9-10.

Not all of the incoming hazardous protons are excluded, but they are slowed down and thermalised to less penetrating energies.

Confirmation that mini-magnetospheres create cavities in the solar wind is shown in the top two panels of Fig. 10. The observations are from two different lunar survey missions with particle and magnetic instrumentation on board. Top left in Fig. 10 is data from the Chinese Change’ E-2 spacecraft, showing the variation in ion density with lunar latitude as the spacecraft passed over a crustal magnetic anomaly. The pile-up of plasma density can be seen to proceed on either side of a cavity in density shown in grey. On the top right panel (a), a similar proton reflectometer instrument on the Indian Chandrayaan-1 which had 2D imaging capabilities, shows how the enhanced proton density forms a ring (yellow-white) around the immediate location of the small patch of surface magnetic field



© E.P Alves, R.A. Bamford

Fig. 9: A self-consistent, 3D PIC simulation of a lunar mini-magnetosphere. The red shows the concentration of protons projected onto the sides and base of the simulation volume. A random selection of higher energy proton trajectories shown in green and magnetic field lines in blue.

GENERATING A MAGNETIC FIELD ON A SPACECRAFT TO CREATE A MINI-MAGNETOSPHERE

It is known from previous work that a magnetic field can be generated on a spacecraft. Our studies so far have not yet allowed for a more comprehensive survey of potential technologies. For more details see Benton 2011, 2012, 2013 and Bamford 2014.

The intensity of the magnetic field at considerable distance

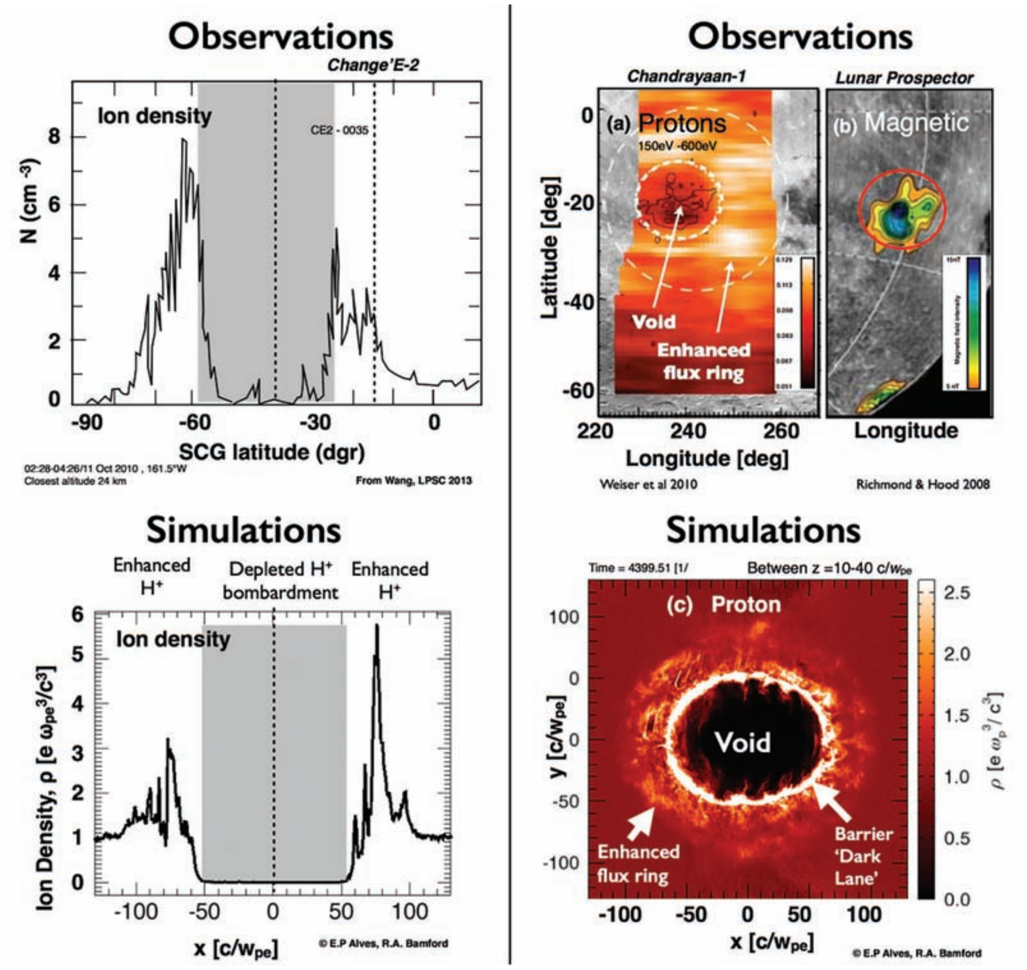


Fig. 10: Confirmation that mini-magnetospheres create cavities in the solar wind is found from the observations from spacecraft (top) passing over the small patches (~300km across) of crustal magnetic field on the Moon. (From Bamford 2016.)

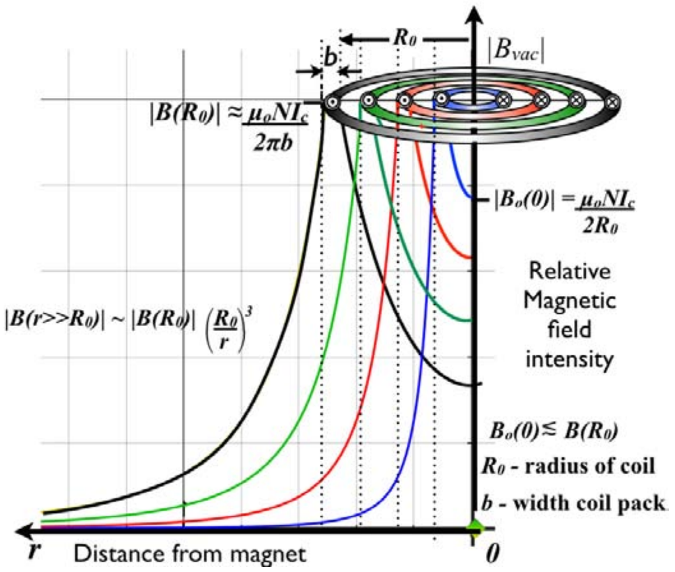


Fig. 11: An illustration of why the long-range strength of the dipole field is improved with a widest possible solenoid diameter.

from the vehicle is a vital parameter in the behaviour of the mini-magnetosphere, since to a first approximation the barrier is located where the magnetic and plasma pressure balance. See Fig. 11 above. Accordingly, the simplest solution is to create a dipolar magnetic field using one or more “flat, round, coils”, i.e. single coils comprising multiple windings.

With superconductors the resource requirements are the cryolant power demands and the charging circuit. Once energized, the power consumption of the coil itself is close to zero. The trade-off characteristics in the design of a mini-magnetosphere coil include; a coil radius as wide as possible (that can be accommodated in the launch vehicle); the highest possible magnetic field; coil mass; cryoplant capability; and an energy storage system to allow it to be run down and re-energized reasonably quickly.

The High Temperature Superconductor (HTS) “tapes” currently available are steadily increasing in their capability to sustain a higher current without quenching (going normal) at a given magnetic field and temperature.

New technologies where high temperature (liquid nitrogen) superconducting materials can be coated onto vessel structures has been demonstrated in prototype (Maher 2004). This would radically alter the balance of trade-offs for a spacecraft.

An example of how a magnetic mini-magnetosphere system might look on a manned interplanetary spacecraft is shown in Fig. 12. Full details are available from AIAA publications (Benton 2011, 2012 and 2013). In these studies only technologies existing at the time of publication were included.

Based on this design, a ballpark figure for a manned mission to Mars shows a requirement for 20kW of on-board power, being redirected to a superconducting magnetic coil system weighing approximately 3000 kg, including cooling. This would reduce the energetic (>50MeV) particle flux by about 20% during a major solar storm (assuming a severe solar storm flux of ~10^{10} protons/cm^{2}sec). Additional augmentations, such as adding extra plasma into the bubble, can greatly enhance its effectiveness, up to 80 to 90% exclusion overall and thus extend the range of energies capable of being deflected.

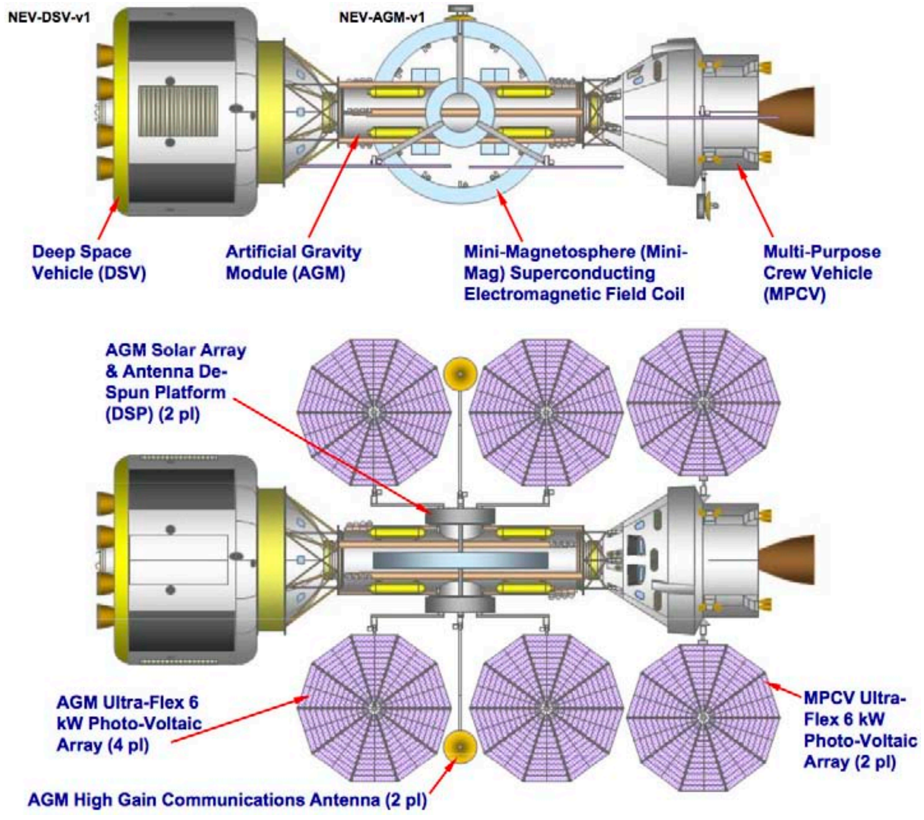


Fig. 12: An example of how a mini-magnetosphere superconductoring coil, with the characteristics presented in text could be incorporated onto a manned interplanetary mission. (© Mark G. Benton, Snr., from Benton 2010 presentation at AIAA.)

CONCLUSIONS

The idea of using active or electromagnetic deflector shielding for radiation protection in space is coming of age. The use of overly simplistic models to describe how the hazardous energetic protons, and other high Z ions, interact with electrostatic or magnetic fields in space led to the earlier, erroneous, conclusion that vast amounts of power were required. The new paradigm shows a much more efficient but very complicated interaction. The Earth's magnetosphere works quite efficiently and it is now clear that miniature magnetospheres with specifications which enable practical construction are within sight in the next 10 years.

Analysis of natural mini-magnetospheres on the Moon shows that the surface has been shielded for millennia sufficient to have altered the colour of the surface; keeping it the original white rather than the usual weathered dark at the locations of surface magnetic field ("Lunar Swirls"). These anomalous surface magnetic fields are small in extent, 10s to 100s km across, with low intensity ~ 300nT magnetic fields, shown by spacecraft transits to be capable of slowing incoming particles and providing tranquil havens from the solar wind.

Laboratory Solar Wind Tunnel experiments have demonstrated that "mini-magnetospheres" dimensionlessly similar to those in space, do form as expected. Added to this, computer simulations using plasma kinetics have shown remarkably good quantitative agreement with both laboratory experiments and lunar mini-magnetosphere in-situ measurements.

As the principles of a new approach practical-sized active deflector shield for spacecraft are demonstrated, the requirement is to optimizing the technology.

In the last 10yrs the progress of superconducting technology continued to higher temperature, liquid deposition a tendency set to continue for the next 10 years and beyond. Multilayer coated conductor films deposited directly on structures means substantial size and weight reduction, higher efficiencies, leading to lower systems costs. The ability to grow continuous high temperature crystalline superconductors directly onto structures has been demonstrated in prototype (Maher 2004). Such lightweight (micron thickness), liquid nitrogen cooled, high field, permanent, superconductors magnets, robust enough to survive launch that only require the power of cooling - offer the potential for a revolution in space radiation mitigation.

It is still not yet certain when the logistically demands would be practical to implement for every circumstance. The analysis of how the mini-magnetospheres preform is very complicated and therefore not suitable for hasty estimates. What is certain is that the estimates power and mass are orders of magnitude different from the vacuum single particle analysis previously thought to be required.

Going forward, the best strategy for ensuring minimum mission burden for an active plasmoid/mini-magnetosphere shield lies in improving our understanding. We already know that a shield works without any magnetic field from the example of comets (Bingham 1991) - here the density constantly replenished by the comet nucleus works effectively. This confirms the principle that the collective electrical properties of the plasma are the active component in the shielding and the magnetic field is there for control and retention.

If humanity intends to expand into space we are going to need active radiation shielding.

ACKNOWLEDGMENTS

The contents of this paper summaries the published work, referred to in the list of references, of Ruth Bamford, Bob Bingham and Barry Kellett, Raoul Trines, Paulo Alves, Fabio Cruz, Luis Silva, Ricardo Fonseca, Alain Cairns, Tom Todd, John Bradford, Mark Benton, Snr, Robin Stafford-Allen and Georgina.

The authors would especially like to thank Scientific Computing Application Resource for Facilities (SCARF) at STFC Rutherford Appleton Lab (ERC 2010 AdG Grant 267841), the European Research Council and FCT (Portugal) grants SFRH/BD/75558/2010 for support. We acknowledge PRACE for awarding access to the supercomputing resources SuperMUC and JUQUEEN based in Germany.

REFERENCES

1. Bale, S. D. et al., 2003, "Density-Transition Scale at Quasiperpendicular Collisionless Shocks", *Phys. Rev. Lett*, 91, 265004
2. Bamford, R.A., et. al., 2014, "An exploration of the effectiveness of artificial mini-magnetospheres as a potential solar storm shelter for long term human space missions", *Acta Astronautica* 105, 385–394.
3. Bamford, R.A., et. al., 2007, "Shields for the starship Enterprise", *Astronomy and Geophysics*, 48.6 : 6-18.
4. Bamford, R.A. et al., 2016, "3D PIC simulations of collisionless shocks at lunar magnetic anomalies and their role in forming lunar swirls", Accepted for publication in *The Astrophysical Journal*, August 2016.
5. Bamford, R.A., et.al., 2015, "Formation of Lunar Swirls", arXiv:1505.06304v1.
6. Bamford, R. A. et. al., 2008, "The interaction of a flowing plasma with a dipole magnetic field measurements and modelling of a diamagnetic cavity relevant to spacecraft protection", *Plasma Phys. and Cont. Fus.* 50, 741.
7. Bingham, R., et al. 1991 "Theory of wave activity occurring in the AMPTE artificial comet", *Physics of Fluids B: Plasma Physics* (1989-1993) 3.7: 1728-1738.
8. Dept, M.D., et al., 2016, "Apollo Lunar Astronauts Show Higher Cardiovascular Disease Mortality: Possible Deep Space Radiation Effects on the Vascular Endothelium", *Scientific Reports*, 6:29901 ,DOI: 10.1038/srep29901.
9. Gargate, L., et.al., 2008, "Hybrid simulations of mini-magnetospheres in the laboratory", *Plasma Physics and Controlled Fusion* 50, 074017.
10. Lin, R. P., et al. 1998, "Lunar surface magnetic fields and their interaction with the solar wind: Results from Lunar Prospector". *Science* 281.5382: 1480-1484.
11. Maher, E., et al., 2004. "Multi-layer coated conductor cylinders—an alternative approach to superconducting coil fabrication", *Superconductor Science and Technology* 17.12: 1440.
12. Nelson, G. A., 2016, "Space Radiation and Human Exposures, A Primer", *Radiation Research*, 185, 349–358 .
13. Turner, R., 2006, "Space weather challenges intrinsic to the human exploration of space". In: Gopalswamy N, Mewaldt R, Torsti J, editors. Solar eruptions and energetic particles geophysical monograph series no. 165: Washington, DC: American Geophysical Union, p. 367–74.
14. Wilson, J., et al. 1997, "Exposures to solar particle events in deep space missions", NASA Technical Paper NASA TP-3668. Washington, DC: NASA.

Received 13 November 2017 **Accepted** 13 November 2017