THE USE OF MAGNETIC FIELDS IN DEEP SPACECRAFT RADIATION PROTECTION

Kent Nebergall
knebergall@ameritech.com
7/18/2006

ABSTRACT

Most studies of the use of magnetic radiation shielding of human spacecraft assume the magnetic field must be centered on the crew module. As such, the crew is exposed to an intense magnetic field with a serious potential health impact in itself.

This conceptual paper examines the idea of using an array of offset magnetic generators spaced around a lightweight crew compartment while that compartment is spinning against its own planetary injection stage for artificial gravity. Centrifugal factors, deployment and support schemes of various models are studied, as well as alignment of individual fields to make the protective qualities as complete as possible with minimal mass. Other designs are also discussed and compared. Finally, a survey of overlapping mission design techniques are considered that could minimize the mass and maximize the protection for early missions in the inner solar system.

THE HAZARD

Any crewed mission to Mars must be shielded from months of radiation from the sun and deep space. While most solar radiation can be handled with 6-12 cm of shielding [Lord, 2006], cosmic rays a serious problem. Cosmic rays are atomic nuclei ranging from hydrogen to iron moving at near-light speeds. Since the particles are usually positively charged, they can be influenced by electric and magnetic fields. Since they carry finite energy and are highly interactive, they can also be blocked with shielding materials [Parker, 2006].

Current knowledge of deep space radiation is so lacking that the actual threat is estimated with up to 600 percent error [Lord, 2006]. Therefore, a vehicle may have 600 percent more shielding than actually necessary, or conversely one sixth as much as needed. While some instruments have been sent and are continuing to be sent into Martian and Lunar orbit, gaps in knowledge are still too great to allow solid engineering of a solution across the full range of solar activity [Choutko, Hofer, Ting, 2004]. Ultimately, we need instruments capable of doing mass spectra and energy analysis of incoming cosmic rays as well as solar radiation.

Earth, Low Earth Orbit, and Cosmic Rays

Contrary to conventional wisdom, the earth's magnetic field does not actually block that much in the way of cosmic rays. Magnetic fields only bend the paths of charged particles moving perpendicular to the field lines. Therefore, the magnetic field provides no protection over the Earth's Polar Regions because the magnetic field there is parallel to incoming radiation. At the equator, where the field is strongest, it only blocks 10 percent of the cosmic rays. The rest of the protection is provided by the atmosphere. Even then, people living on earth are exposed to the equivalent to two chest x-rays per year from cosmic rays alone [Parker, 2006]. The principle benefit of the magnetosphere is in blocking solar wind, not cosmic rays.

This has two implications. First, critics of deep spaceflight who indicate that the International Space Station is protected from radiation by the magnetosphere are only correct about solar wind, which can be blocked with a few inches of shielding in deep space. Crew members are protected by ten percent at the equator, even less during parts of the orbit at higher latitudes. They are also protected by the earth itself, which takes up between 140 and 141 degrees of the celestial sphere as seen from the ISS, or 39 percent. (This was determined by running the program Celestia, setting the view from the ISS, selecting the Earth as the observed object, and running through 10 days at high speed while watching the percentage meter.) We can add a degree for the atmosphere blocking slightly more of the "sky" as seen from ISS, making 40 percent. With the remaining sky (60 percent) having its cosmic ray flux reduced by between zero and ten percent by the earth's magnetic field, that leaves an astronaut in LEO receiving between 54 and 60 percent of the cosmic rays they would in deep space, depending on latitude. The space station then becomes an excellent example of how much damage cosmic radiation is NOT doing to crew members. It also means that a protection system does not need to be complete to match the security of LEO, it only needs to block between half and two-thirds of incoming cosmic rays. Given the long flight time, it should ideally block 80 percent or more.

When engineering a solution, we need to look again at the hazard. Cosmic rays consisting only of a proton are very numerous and can more readily be blocked with a field, but an iron nuclei, while rare, can do far more damage if it impacts a crew member [Parker, 2006], especially if they hit certain small parts of the brain [Lord, 2006]. So by stating that solutions do not need to be as extreme as the straw-man systems attacked by critics, this does not mean they need to be minimal. We are simply establishing boundaries within which engineers may work on cost to benefit ratios and realistic risk assessments.

THE MAGNETIC ARRAY PROPOSAL

The Solution Space

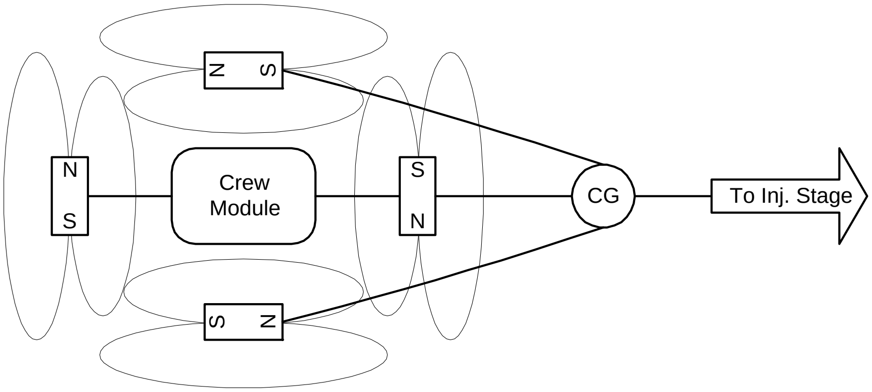
Any solution involving magnetic fields should…

- Do something about the fact that the poles of the magnet are unprotected to any radiation coming in directly.
- Minimize the magnetic flux at the crew module itself.
- Maximize the effect that any given magnet has on the incoming radiation.
- Work on a small spacecraft spinning against its injection stage for artificial gravity.
- Take up minimal resources in terms of mass, volume and electrical power.
- Require minimal maintenance and involve manageable complexity.
- Be small enough that experimental, robotic versions can be launched as proof of concept.

The Proposed Design

The solution proposed here combines a framework of lightweight superconducting electromagnets arrayed on a framework around the vehicle. After the vehicle is sent on its interplanetary course, the injection stage and mission module are separated and a tether is extended between them. The vehicle is then spun up to provide artificial gravity for the crew. In the gap between the crew module and the injection stage, a folded array of superconducting magnets, cables, and struts is deployed. This consists of a series of rings, arranged roughly into a sphere, hanging in the gap between the crew module and the center of rotation. The crew module is then retracted along the spin cable so that it is situated at the center of the sphere of rings (called the magnetic array). This array is energized in such a way that any particle entering the space of the crew module must penetrate roughly perpendicular to a magnetic field before reaching the vehicle. The magnets are matched in such a way that very few if any gaps between magnetic fields. The structure uses magnetic repulsion between array elements to keep the structure "inflated" while minimizing the structural mass, since cables to compensate for tension weigh far less than girders to compensate for compression. Sensors and computer controls keep the field on each magnet optimized to allow for the power available, the lifespan of the structural elements being used, and the current radiation environment.

FIGURE 1



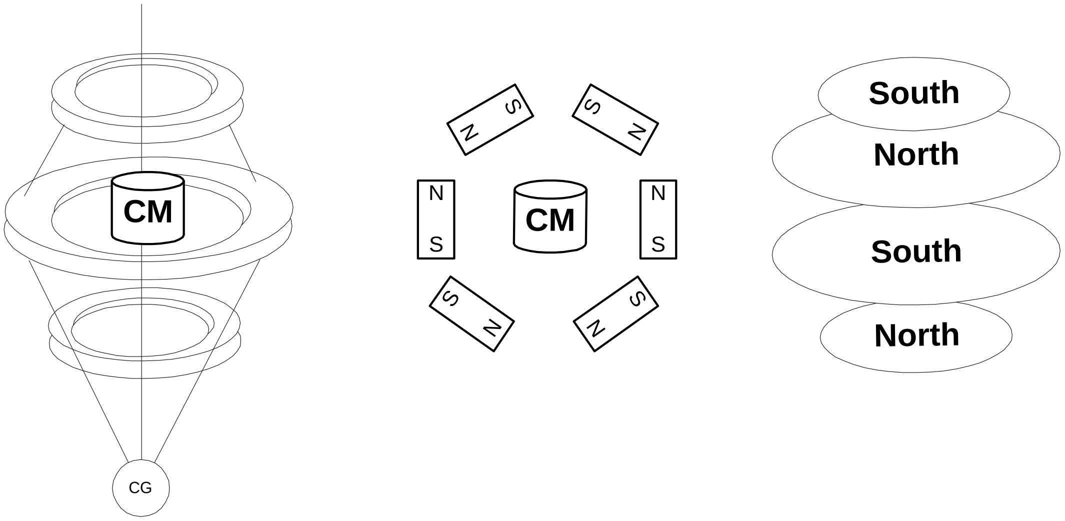
First, let's look at a simplified version with only four magnets operating in two dimensions. By putting the field outside the craft, a ray must penetrate the field over its entire volume of flux before it can hit the crew module. A cosmic ray will only be deflected if it crosses a magnetic field perpendicular to the field lines. If a cosmic ray comes in directly at a magnet, it receives the full flux of the magnet before it can potentially reach the crew module. If a cosmic ray passes half-way between two magnets, the fact that the magnets are arrayed to push against one another increases the flux in the space halfway between fields, again adding to the force applied to the cosmic ray. Any cosmic ray entering a magnet's field via the pole will fly alongside the craft rather than into it, missing it harmlessly.

Physics, Strengths, and Weaknesses

The interesting thing is that with fields going from north to south on both sides of the magnet, the particle is vectored in the same direction both before and after passing the magnet itself. By placing the magnets in an array like this, it maximizes the exposure of the particle to the field lines before the particle can reach the crew module.

Where things get strange is at the poles. As a particle crosses into the field, the field lines run from north to south. However, once the particle is above the pole, field lines coming out of the pole are actually flowing the opposite direction before they move out and loop back. The result is that while influenced, particles flying over a pole will vector in one direction, then in the exact opposite direction, and then back and forth again after crossing the pole. While imprecise entry paths and energies will still reduce radiation arriving at the vehicle, it won't prevent entry, simply make it chaotic depending on the direction of arrival and relative charge and mass. To minimize this, the magnets need to be made as long as possible and the gaps between them as small as possible.

FIGURE 2

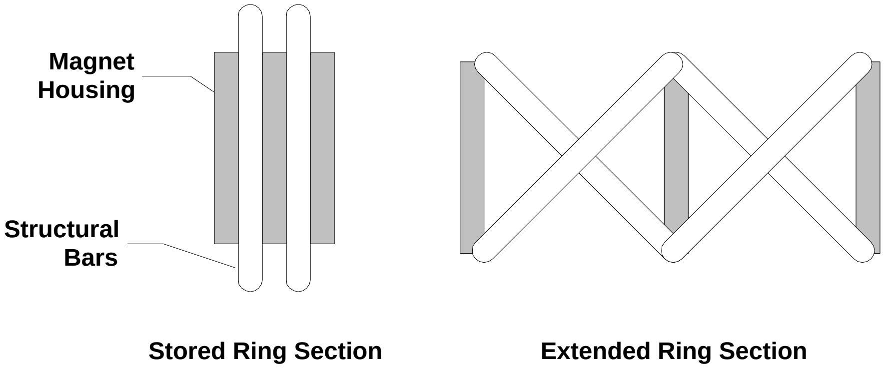


Let's examine a more complex three-dimensional design. The illustration on the left shows the fully deployed array with the center of gravity for the rotating craft at the bottom (the injection stage is not shown). The middle illustration shows the magnetic alignment of each ring in cross section. Note that all fields are repelling the adjacent rings. These patterns are shown on the right. This allows us to carry the symmetry of the simplified design in Figure 1 into three dimensions, because the alignments break down into being the same at each cross section. There is one engineering issue with this, however.

Deployment Mechanism and Torque

The problem with this design is that magnets, aligned next to each other and with the poles facing perpendicular to the line of magnets, have a tendency to allow the attractive force of the opposite poles to pull them into a line parallel to their arrangement. This force is increased as the magnets are arranged closer together.

FIGURE 3



What is needed is a compressive structural element that will be aligned to prevent this from happening. Fortunately, this falls exactly in line with an accordion-folded deployment mechanism. When stored for launch or re-entry, the discharged magnets and their structural elements are folded closely, as shown on the left. When deployed, the elements are extended and locked into place. Each structural element, therefore, is placed exactly where it needs to be to prevent the attractive and repulsive loads from destroying the structure. Also note that the attractive and repulsive loads are relatively balanced in terms of whether the magnet will be pulled to the left or right. Adding sensors and load balancing the charge on each magnet can help minimize this load and therefore the structural mass of the ring sections.

Since the ring-to-ring forces are repulsive, the load here is tension-based rather than compression or sheer. As such, the main structural elements are cables, which are much lighter than beams needed for the other two forces. While elements are also connected by accordion-fold elements for even spacing and so on, the actual loads are handled by cables.

Trapped Radiation Management

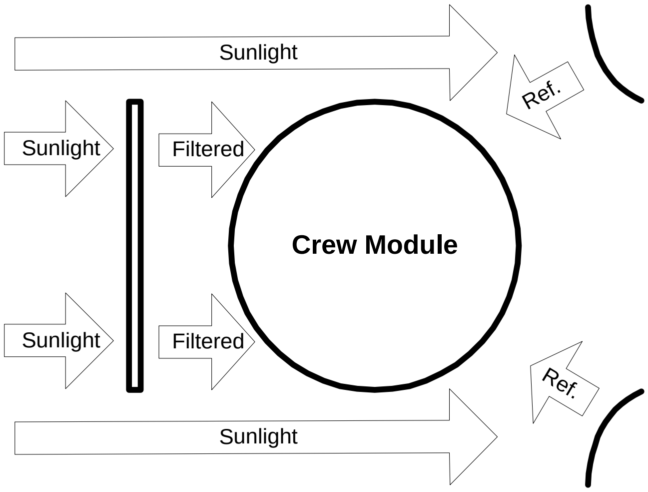
The magnetic array is in direct contact with the solar wind, and therefore will build up some form of “radiation belt” with or without cosmic rays. Since a particle in a constant field at the same energy level as the field will enter a stable "orbit" within that field, the overall field intensity is varied slightly so that trapped particles may "leak" into space during quiet periods. The system itself may emit cyclotron radiation from some particles, so this must also be considered in the balance of "venting" versus maintaining trapped particles. The radiation fields would also need to be relieved before any EVAs take place, and before the crew module was released from the array on arrival at the destination planet.

The magnetic array design has strong overlaps with the M2H2 solar sail concept, and a future design could integrate the two concepts. Even if this design is not currently considered an M2H2 solar sail, the impact of the solar wind on the magnetic field in navigation would need to be analyzed and compensated for.

Power, Temperature Management, and Rotation

A key advantage to a magnetic field-based protection system is that if one can use superconductors the system requires very little ongoing power to maintain itself. Advances in higher temperature superconductors approach the temperature that can be maintained simply with sunshades in space, so lightweight cooling systems for each magnet or set of magnets is potentially feasible. The sunshield on the James Webb Space Telescope, for example, can cool a large area to 40 degrees Kelvin, and do so a 1.6 million km from Earth, without any other cooling mechanism. Solar energy is roughly 40 percent of that value when the vehicle reaches Mars, so the efficiency of the cooling system is increased with distance. To avoid having to spin the shields (and any solar power arrays) with the rotation of the vehicle, the craft would be turned so that the spin axis points toward the sun at any given time. This makes the system far simpler than it would be otherwise.

FIGURE 4



Temperature control for the crew module would need to be managed, since one side would always face the sun. Even the spent injection stage should have some passive thermal management to prevent fractures. A small sun shield for the “day” side and small sun reflectors for the “night” side of the vehicle would resolve the temperature management issues passively, and could be integrated with solar collectors and radiators. The anchor points for the solar management arrays could also be used as anchor points for the magnetic array itself.

A Reusable Rigid Cage

Let’s assume for a moment that the mass of this system becomes so great that it requires a separate launch, but that no lighter mass systems are found to be workable. The cage could be launched with an aerobrake on one end. It could then be extended in earth orbit, tested, then docked with a crew cabin launched separately. On arrival at Mars, it could be undocked, retracted and allowed to aerocapture separately into the Martian atmosphere. It could then be stored in orbit, extended for use with the Earth Return Vehicle, then captured the same way at Earth for refurbishment and reuse.

The only penalty would be the need to bring enough propellant for both the radiation shield and the human spacecraft. However, this is far from insurmountable. Even in the unlikely possibility that the craft had the same mass as the crew module itself, it would simply mean one additional launch from earth for an additional third stage, and possibly a robotic ERV from Mars used purely to bring additional fuel for Trans Earth Injection.

Magnetic Faraday Cage Design

During the literature search for this paper, I found the work of MIT scientists H. Hofer and S.C.C. Ting. They have proposed a “magnetic Faraday cage” design for Mars missions. The concept is to surround a small crew cabin a second vessel of superconducting electromagnetic rings that cancel out their own fields within the structure. This is modeled after their work on the Alpha Magnetic Spectrometer (AMS) for the International Space Station [Choutko, Hofer, Ting, 2004].

Their design addresses many of the same ideas as this distributed design. It zeros the gauss experienced inside the cabin, operates with end-caps that prevent radiation from coming in the poles of the main magnetic field, and does so with superconductors to minimize power consumption. It can also be spun for artificial gravity and has a mass (at least for the coils) that is 9.5 tonnes, even for a “larger” crew cabin (4.5 by 7 meters).

There are issues with the AMS-derived paper that appear unaddressed. First, while their diagrams of the AMS include massive liquid helium tanks for cooling the coils, the diagrams for the Mars Magnet leave this off, leaving one to wonder where the cooling is derived from. Their design also comes in several sizes. A larger design has a crew cabin diameter of 4 meters. However, with the coils around it, the vehicle grows to nine meters, and this assumes the helium to cool the coils is kept in the zone designated for life support and other functions behind the coils, rather than outside the coils as in the AMS design.

FURTHER INVESTIGATION

Continued Research

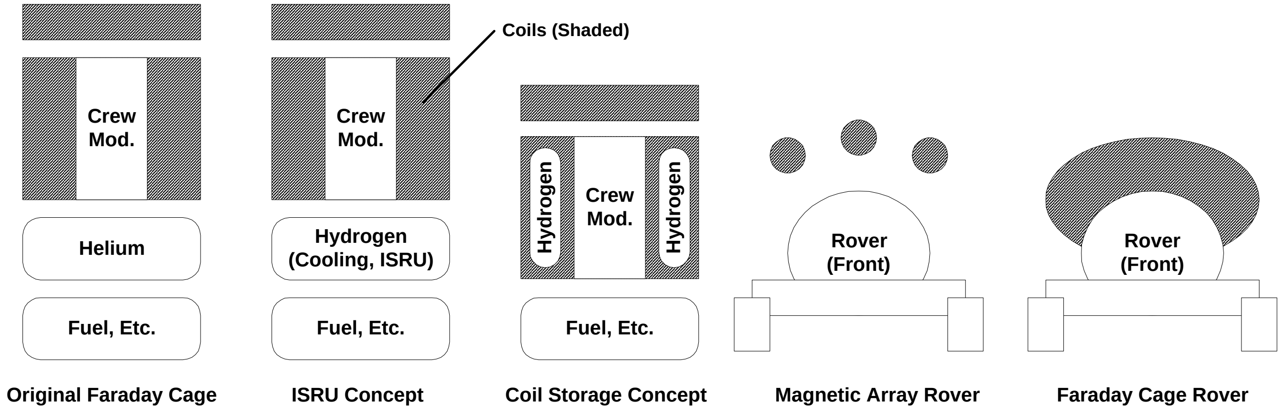
The AMS appears to be on the third from last shuttle mission for ISS construction. This instrument is critical to characterize the energy, composition, and charge of cosmic radiation. We need this data, and years of it, to wisely design crewed spacecraft for long durations on the Moon or for interplanetary flight, regardless of the solar cycle. It also forms a prototype for the "Mars Magnet" designed by Hofer and Ting. By extension, any future magnetic shield design would benefit from the launch of this instrument, and any non-magnetic shield would benefit from the characterization of the cosmic ray threat data derived from running this instrument.

There is a radiation hazard instrument (MARIE) on the Mars Global Surveyor probe that returned data until taken offline by a solar flare. That instrument is now acting as a relay for the Mars rovers currently active on the planet [Garget, 2006]. Ironically, the sooner the rovers die, the sooner NASA can attempt to reactivate that instrument to give long term data required for human exploration, so it won't be entirely bad. A similar instrument is being included in the Lunar Reconnaissance Orbiter. This will also characterize secondary forms of radiation emitted by the moon itself when struck by solar and cosmic radiation.

Continued Engineering

If the magnetic array design discussed here appears promising, the next step would be to characterize how a vehicle with a distributed magnetic field would resist radiation of different charges, masses, and velocities would interact with the shield when approaching it from different directions. This could be simulated effectively in software. When an optimum arrangement for magnets and the strengths required is characterized in this way, the task of engineering those magnets and the deployment system could begin. If the technology is available, a prototype could be tested using an accelerator on earth. A refined version could then be launched to a position outside the Earth's magnetic field for long-term tests. The crew cabin would be replaced by a sensor array. Since the magnetic field would be well understood, the prototype would effectively double as a large cosmic ray observatory. Like AMS, it would give an excellent platform for understanding not only the radiation threat but how to engineer a solution to the problem.

Hybrid Concepts and Mission Design



Finally, consider the implications of these three concepts (magnetic array, magnetic Faraday cage, and bulk shielding) for mission design.

Can hydrogen be used as a coolant for superconducting magnets instead of helium? What implications does this have for In Situ Resource Utilization, since five or more tonnes of hydrogen need to be brought to Mars anyway? If it appears that if this can be arranged, it would be the mirror image of Mars Direct – a hab would be sent ahead uncrewed, followed by a crewed earth return vehicle carrying hydrogen for the propulsion production once there and cooling of the coils en route. Hydrogen cooling for superconductive power lines is already being considered for a hybrid electric/hydrogen power grid for the US [Grant, Starr, Overbye, 2006]

If hydrogen can be used, or even if helium is used, can it be stored inside the coil itself on the Faraday cage design? This would use otherwise empty space while providing a natural moderator for any particles coming into the system – they would be bent by the field while simultaneously being weakened by the moderator. If the moderator is hydrogen, there are minimal secondary particle effects.

If the Faraday cage is the only solution, we would want to keep the number of cages to a minimum. That implies that the best mission is to have a complete Faraday cage for the transit vehicle, which would be used for crews going to and from Mars but left in orbit. A hab on the surface would have a top-only Faraday shield and would use a crater rim and the shallow incidence of particles through the atmosphere to give the remaining shielding. Finally, and a minimally shielded transfer vehicle would take crews between the two. This would definitely use ISRU, and may even be used to carry not only fuel to carry the crew back to orbit, but enough power to boost the crew and the Faraday-equipped transit vehicle back to Earth.

Given all this complexity, it could also be reversed. The original design for Mars Direct was a single vehicle that would do everything in one shot – crew transport, hab, and earth return. Would assembling such a vehicle in space take fewer launches than the alternatives?

Could the Faraday cage design be broken down into quarters and launched as a stack, then mated with a crew cabin in orbit? A quartered system could potentially be removed and reused on future flights. Also, a surface hab could simply use the end-cap for radiation protection on the surface and leave the coils in orbit. This would reduce the landing mass of such a vehicle while leaving the outer coils where they could be used by the crew on return.

If a long range rover needs magnetic protection, could the crew cabin and shield of the rover also be used as the Earth Return Vehicle cabin? The rover could be made in two segments, and the crew/magnet segment could be hoisted into an horizontally-configured ascent vehicle. This has many implications – by making these vehicles modular, you now have a truck/rover (the rover without the hab) and a cargo lander/ascent vehicle (the ascent vehicle without the hab). Ultimately, could the magnetic array design be used in any situation where a full Faraday cage is not practical but some protection is desired, such as mobile and transportable shelters?

CONCLUSION

This survey of both the Magnetic Array and Faraday Cage designs, combined with hydrogen storage, provides a set of questions that should be investigated when discussing long range spaceflight and surface habitation. It also presses the issue that technology is not static – it seems likely that the crewed missions will use a conservative system like the Faraday Cage at first, hopefully with some of the innovations listed here to minimize the mass. Then when higher temperature superconductors mature, consider a lighter arrayed system to save weight or provide protection for lighter craft on shorter missions such as rovers. Regardless, and the spate of recent magazine articles pushing the meme of the brass heaven not withstanding, we are far from exhausting all our options when finding practical solutions to this issue.

REFERENCES

M. G. Lord. Impossible Journey? Discover magazine. June, 2006.

Eugene N. Parker. Shielding Space Travelers. Scientific American magazine. March, 2006.

V. Choutko, H. Hofer, and S.C.C. Ting. The AMS Experiment and Magnetic Faraday Cage for Human Space Exploration. August, 2004. http://aoss.engin.umich.edu/Radiation/presentations/index.htm

Jacqueline Garget. Who Knows What Dangers Lurk in Space? Astronomy magazine. March, 2006.

Paul Grant, Chauncey Starr, and Thomas Overbye. A Power Grid for the Hydrogen Economy. Scientific American, July 2006.