2. Meteoroid and Cosmic-Ray Protection

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Meteoroids

In terms of visual impact, I suppose the most frightening type of disaster in space conceivable would be a ten-ton meteoroid colliding with a large colony, followed by explosive decompression and death for all inhabitants. Let me quickly assure you that that eventuality is only likely to be seen in future versions of movies such as "The Towering Inferno." The real meteoroid problem is basically one of identifying occasional minor leaks and repairing them in some economical fashion.

The first question to ask is: What is the flux of meteoroids of a given mass? Data come from three sources. The first and least satisfactory is photographic and radar observations from Earth, the second is measurement from space-based instruments, and the third is lunar impacts as measured by the lunar seismometer network

In the meteoroid mass range of a microgram to one gram, spacecraft sensors provide abundant data, and for masses above ten kilograms, the lunar seismic network is believed to have 100% efficiency. The Earthbound data are subject to large corrections, but agree with the NASA data at ten grams mass.

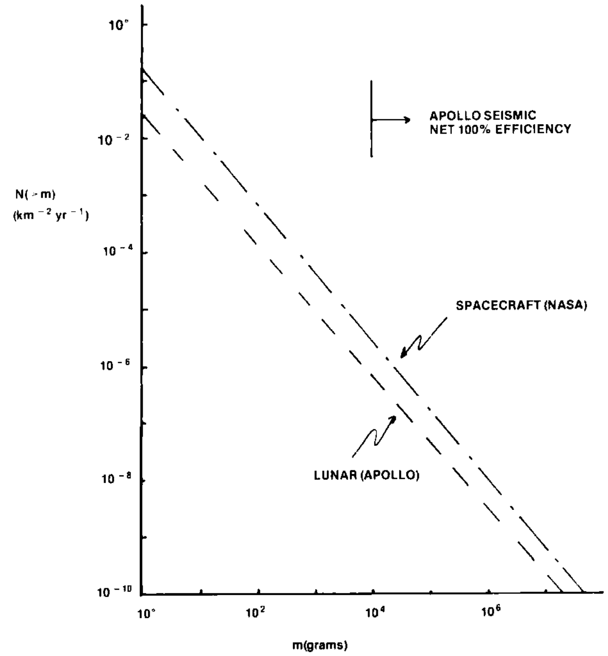
Figure 109 shows the distribution for meteoroid masses. I have not shown the Prairie Network data here, which is the Earth-based material, because it is subject to large corrections of an uncertain nature. The meteoroid structure most commonly found in space is a conglomerate of dust, bound together by frozen gases – a "dirty snowball" – as opposed to the stony or nickel-iron rock which reaches the Earth's surface after going through the atmosphere.

The second question to ask is: What effects would varying sizes of meteoroids have on a Model 1 colony? We can assume that anything heavier than about one ton would do very serious damage, for example, break one of the hoops. Somewhat less mass than this would probably result in a hole and extensive damage, but limited to the area of the hole. The main problem for the colony would be the immediate repair of the hole before much of the atmosphere could escape. Calculations by Daniel Villani at Princeton show that the leakdown time to 40% of the initial atmospheric pressure is eight hours for a hole two meters in diameter.

A more common occurrence would be the breaking of window panel by a small meteoroid. This would result in a leakdown rate of about one percent of the atmospheric pressure per hour. We estimate such window-breaking to occur from strikes by meteoroids having masses down to 0.3 gram. Below this mass value, the main problem would be a "sandblasting" effect on the windows, which, over many centuries, would reduce the transparency to light and would eventually necessitate resurfacing of the windows.

Table 25 lists possible meteoroid "disasters", showing the amount of time one expects before any specified disaster occurs. The one-ton meteor, which is the really catastrophic one, is a rare oc-

Figure 109. Cumulative Distribution of Meteoroid Masses.



currence. Even 100 grams, which will break a window and perhaps create a good-sized hole if it comes through a metallic land-area structure, strikes only once in seven thousand years. The most frequent problem is the abovementioned 0.3-gram strike, once every three years. That produces only the minor problem of detection: has a panel broken? If so, where? And then getting to it and covering it up. Hence the risk to human life in space stemming from meteoroid strikes appears to be quite low in comparison to accidents and natural disasters here on Earth.

Cosmic Radiation

At the other mass extreme, we now consider the effects on people in space from the lightest particles: cosmic rays.

Streaming out from the Sun and inwards from the galaxy is a large collection of charged particles called "cosmic rays." Cosmic rays are predominantly protons moving close to the speed of light, but it is likely that every element of the periodic table is included in this onslaught.

Table 25. Risk Factors for Model I from Meteoroids

Mass	Time to Occur	Worst Effects
1 ton (metric)	2.5 × 10^8 years	severe damage
100 grams	7,000 years	10 hour leak-down to 40% of one atmosphere
0.3 grams	3 years	loss of window panel, 1%/hour leak-down

Figure 110. Cosmic-ray energy spectra of the more abundant nuclear species as measured near Earth. Below a few GeV/nucleon, these spectra are strongly influenced by modulation within the solar system. The different curves for the same species at those energies represent measurements at various levels of general solar activity, the lowest intensity being observed at the highest activity level.

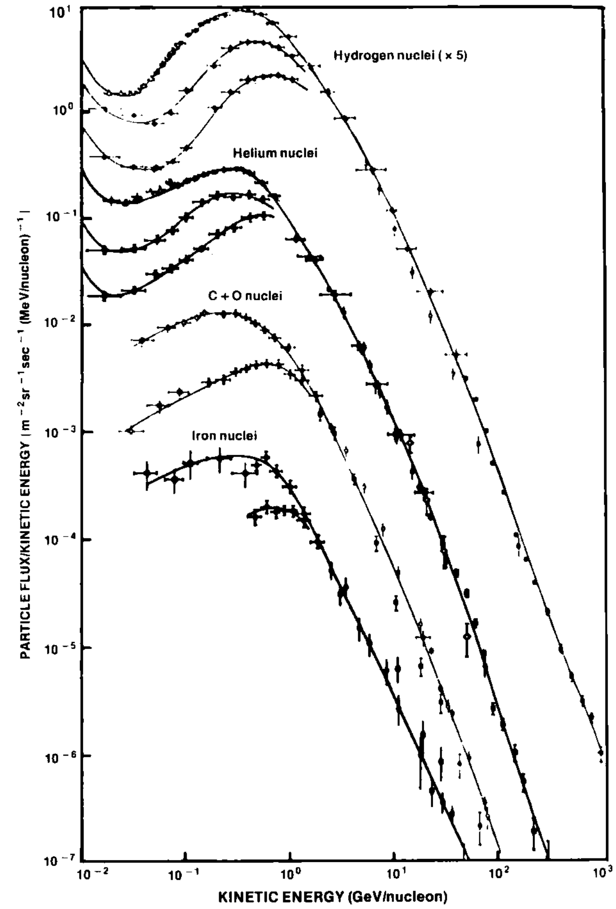
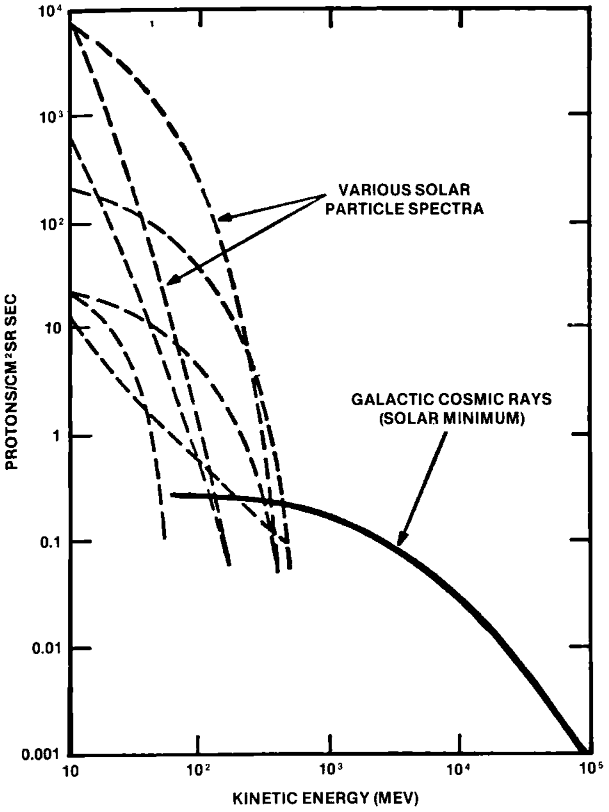


Figure 110 shows how these various components vary with energy per nucleon. The lower curve branch for each species reflects the peak effects of the solar wind in "sweeping away" the less penetrating particles when the Sun is very active. For a point of reference, the rest energy (mc^2) for most particles is at about 1 GeV; above that point, where the curves start to slope down to the right, are relativistic particles.

When the Sun is at its most active stage, as when a giant flare or solar eruption takes place, then the cosmic ray flux contains massive amounts of added particles as seen in Figure 111. These added par-

Figure 111. Energy spectra from several moderate-size events compared with the galactic cosmic-ray spectrum.



ticles stream out of the Sun and cause the massive ionospheric disturbances that disrupt communications and create strong aurora effects. For lightly shielded structures, solar flares constitute a serious danger to personnel.

Cosmic ray particles endanger human beings because the passage of charged particles through tissue causes the breaking of chemical bonds. The damaging power of a charged particle is closely related to its "ionizing power", which measures how many chemical bonds per unit of body mass are broken and thereby gives at least a rough measure of the tissue damage sustained and the chances of genetic mutation.

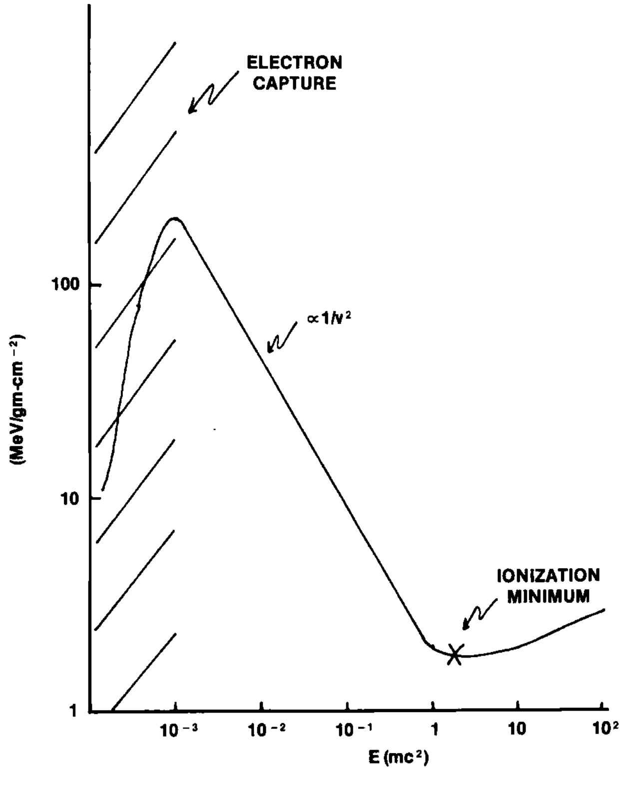
Figure 112 plots the ionizing power of protons in silicon dioxide as a function of proton energy. Since the units of ionizing power are in units of mass traversed, the same numbers are reasonably accurate for all low-atomic-number (Z) matter; for example, human tissue. This basic curve also holds for any ion species when the vertical axis is multiplied by the ion's Z^2.

The essential result is that the ionizing power increases as the particle energy decreases, so the more slowly moving particles are the most damaging. In the extreme relativistic energy region, the damage effects are basically constant. At the low-velocity end, the particles are removed by "electron pick-up," which neutralizes the charged particles.

The annual radiation dose that the general cosmic ray background gives an unshielded person, aside from the occasional solar flare outburst, is about one rem per year. This is not a high level of radiation: perhaps about twice what jet flight crews receive annually and only about one fifth the government's recommended dose for radiation workers. If the total dose were the only relevant radiation variable, then the problem would reduce to the simple issue of providing solar flare monitoring and intensive shield areas to be used only during the several hours of solar flare activity.

The problem, however, is more complex, because included in the general cosmic-ray flux are substantial amounts of totally stripped iron nuclei. When a fully stripped iron nucleus is traveling below about half the speed of light, its ionizing power is several thousand times that of minimally ionizing protons. At this level of ionizing power, the passage of a single iron nucleus through the body destroys entire columns of cells lying along its trajectory. The total amount of energy dumped in

Figure 112. Ionizing power of protons in silicon dioxide.



the body by the particle is small, but its concentration is intensive over localized regions of the body. We don't yet know how bad this form of radiation is in terms of increased rates of cancer, for example, but we can calculate the loss of non-reproducing cells, such as spinal-column nerve cells, that any given exposure will cause. As an example, a recent article in *Science* has estimated that the Apollo 12 astronauts, during their two-week voyage to the Moon, lost between 10^{-7} to 10^{-4} of their non-replaceable cells, e.g., neurons. Projecting these data to a two-year mission to Mars and back, the fraction of lost cells could reach several percent. These effects, applied to young developing organisms such as children, could prove far more catastrophic.

Thus we must set a dose limit for exposure to heavy ion radiation for the Model 1 colonists. We have arbitrarily chosen the limit to be a dose equal to the amount the Apollo 12 astronauts received in two weeks; i.e., if a colonist is expected to live in Model 1 for thirty years, we must provide enough shielding to guarantee he will not accumulate the Apollo 12 dose until thirty years has passed. This brings us to the issue of practical shielding in the early space colonies, which lack the intrinsic shielding mass the later models will possess.

The first method of shielding is simply to use compacted Moon rock to surround the living quarters with spot shielding. The shielding calculations, including such factors as nuclear fragmentation, particle slowing-down, and creation of secondary radiation, indicate that 132 g/cm^2 of Moon rock would protect again the heavy ions and create an annual dose of about 3 rem.

But even though mass can protect human beings from cosmic rays and even solar flares, it is not a very effective or elegant way to achieve protection. Among the awkward aspects of mass shielding are the following:

- It adds considerable mass to the protected structure over and beyond the purely structural requirements for mass. Succintly, "mass is money."
- At the required thickness of around 150 g/cm^2, cosmic ray secondaries are produced copiously. Thus, adding mass causes the year's dose of overall ionizing radiation to go to about 3 rem, when an unshielded environment would only cause about one rem per year.
- The peak flux of iron nuclei occurs for velocities very close to the speed of light. Adding mass slows down these particles to below half the speed of light, the point where tissue damage becomes very serious. Thus, even though we add mass specifically to stop the iron flux, in a sense it only makes the basic problem, the elimination of slow rather than fast particles, more difficult.

We therefore conclude that simple mass shielding of cosmic rays would not be either economic or effective.

Examining other alternatives, we recognize first that it is the slow particles, both the iron cosmic rays and solar flare protons, which cause the most damage to human beings. Hence moderate magnetic fields could do the shielding job. A magnetic field distributed in space can protect against both iron nuclei and solar flares if its intensity multiplied by its spacial extent is around four tesla-meters. For objects with dimensions of the order of kilometers, peak field intensities needed are only of the order of a hundred gauss, spread over such dimenions.

As a concrete example of such an "active shield" approach, I have calculated roughly the parameters needed for a magnetic deflector which consists simply of coils of superconductor on the endcaps of a Model 1 cylinder. Table 26 shows the parameters of such a shield. Four hundred gauss, since people are not made out of iron, is not a very bad field to live in. The peak energy is a little high, however, and protection must be provided against an energy short-circuit through a single point. An attractive feature of such a field is that after the 90-second power-up period, no further energy is required to sustain the field.

A more detailed sample design for a magnetic

Table 26. Model I Magnetic Deflection System Parameters

Parameter	Value
Radius of endcap coils	100 meters
Central field strength	377 gauss
Current in coils	6 × 10^6 amps
Required mass of super-conductor	470 tons (metric)
Field energy	9 × 10^9 joules
Field creation time at full power station power level	90 seconds

Table 27. Toroidal-Geometry Station Shield System Parameters

Parameter	Value
Major radius of station	100 meters
Minor radius of station	10 meters
Number of conduits	63
Superconductor mass	38 tons (metric)
Current in conduits	3×10^5 amps
Field Energy	2×10^7 joules
Field creation time	20 seconds
Magnetic pressure	– 14.3 pounds per sq. inch

shield postulates a toroidal space station with a major diameter of 200 meters and a torus cross-section (living-quarters) minor diameter of 20 meters. Surrounding the living space are 63 superconducting conduits which carry current parallel to the toroid's major circumference. This geometry produces very little magnetic field inside the living-quarter tube by symmetry, but it does create a very strong field outside the tube walls. It is this outside magnetic field which diverts flare protons and cosmic-ray iron nuclei away from the living spaces. This geometry has a further advantage in that since it surrounds the living quarters with a cold environment (to keep the superconducting system cold), any gases leaking out from the interior would be cold-trapped. Since they would freeze to the sides of the wall, they would eliminate atmosphere leakage problems from the station structure, a major consideration for resupply.

Table 27 shows the parameters of such a shield system. It requires only about 38 metric tons of superconductor mass to provide the shielding required, since the actual superconductor need only have a radius of about 6 mm.

The field energy is 2×10^7 joules and it takes twenty seconds to establish, assuming ten kilowatts per person for a thousand people. The last parameter in Table 27 is rather interesting. "Magnetic pressure" is the result of the interaction of the currents flowing in the conduits with the outside magnetic fields they create, causing an inwardly directed pressure which squeezes the tube. At 14.3 psi, if the station's internal air pressure were one Earth atmosphere, the magnetic pressure would very nicely balance the internal pressure. This numerical agreement was purely coincidental.

In summary, I think it is safe to say that careful attention to engineering can overcome the problems of meteoroid and cosmic-ray protection, even in the early space colony "construction-shack" models.

DISCUSSION

Q. *What's the strength in gauss of the second field that you described?*

A. I assumed that the field was distributed across a hundred meters. At four tesla, that's 40,000 gauss-meters. The central field is then 400 gauss, but as you get in closer to the actual superconducting wire, it increases inversely with the radius. So there is a very strong field right at the superconducting conduit, limited, of course, by the maximum field which does not destroy the superconducting property. That's what determines the superconductor's radius. For niobium-tin, with a safety factor of two, that's about ten thousand gauss.

Q. *This field is supposed to slow down the slow-moving particles. Why doesn't it slow down fast-moving particles and make them slow?*

A. "Slow-down" isn't quite an accurate description. All the field does is make the particles go in circles. A slower particle goes in a smaller circle than a fast particle. A very fast particle would be bent slightly by this field but nevertheless will come zipping right through. A slow particle would be bent enough so that it would turn away. To be honest, I haven't done detailed trajectory analysis to see exactly how the turning will go, but I think for a dipole field, for a hoop like this, the particles would zip down the center quite freely. I wouldn't want to live in the center of the torus, but the particles would be nicely diverted away from the living area in the outer circumference.

Q. *Did you look at long-term effects of the field interacting with the Earth's field?*

A. I believe that L5 is sufficiently far away that there's no Earth field left. But there will be effects of the solar wind and other phenomena. I have not tried to estimate these. This was just a crude, quantitative estimate to show that at least it's feasible to think in terms of using low-mass active shields.

Q. *Does the magnetic field have any implications for docking maneuvers and supply ships?*

A. If they are made out of anything with steel or iron it has considerable consequences. I assume, though, that most space ships would use non-magnetic structures.

Q. *Will the inward magnetic-field pressure tend to cause structural instabilities — buckling — of the wall?*

A. I never seriously thought about using the field to balance off the atmosphere. If it takes more mass to hold off the field pressure than to hold the atmospheric pressure, it's obviously not worthwhile. In this case, it would appear that the two forces cancel each other, so the structure can take it nicely.

Q. *It seems to me you have the wrong sign on your magnetic pressure. There is a theorem that the integral of tension times volume to contain a magnetic field is given by the energy of the magnetic field. If you have pressure contained on the one hand, and the magnetic field contained on the other, they will add, not subtract.*

It might be that the tension around the small ring is reduced, but the tension around the large ring certainly isn't. It is not a gain.

A. Yes. I was discussing only the hoop strength of the minor diameter.

Q. *Some years ago we pointed out that you gain a very large advantage in the magnetic field effect if you use that field to hold electrons in orbit along the magnetic field lines. This develops high voltages, of the order of several hundred million volts, to do exactly what you want — accelerate the slow particles without affecting the large particles. That is, your field will trap electrons to create a potential with the space vehicle which will be several hundred MeV above the surroundings. The decelerating electric field is enough to accomplish the effect that you wanted.*

A. That sounds very interesting.

Q. *What temperature do the superconductors operate at? Did you look at what kind of radiator area you would need for heat rejection? Heat loss is a big problem in a ring station to begin with. To keep the superconductors cooled, you'd need a huge radiator area.*

A. I was assuming about half the critical temperature for niobium tin, which, I believe, is around 18K. It is no real problem to hold 4K. I was assuming that there would also be use of super-insulation to minimize heat leaks. I haven't looked at the detailed refrigeration problems.

Q. *Why don't you wait until the heavy nuclei have actually penetrated a moderate mass shield, perhaps 100 g/cm. A field of about a kilogauss would then turn the nuclei, with a radius of the order of a meter or so, and send them back into the material as many times as is necessary.*

A. There's a problem there, because the flux of the slow particles is actually much below the flux that move at about the speed of light. So if you use 100 g/cm^2 you've nicely succeeded in slowing down the peak flux to where it hits with much more damage potential than it had to begin with.

Q. *Since your space station is rotating, would you be creating some low-level synchrotron radiation? You'd have, in effect, a little pulsar up there.*

A. Since the rotation is axially symmetric with the field, I don't think so. There *would* be some interesting electromagnetic effects. For example, the collapse of the field in the event of a short-circuit has some interesting effects, but I think at very low frequencies.

Q. *Why not just use an electron gun to accelerate the electrons enough to put them into an escape orbit?*

A. You cannot do that, because the conductivity of space is too high. It would require too much an energy load. However if you reduce the conductivity immediately around the space vehicle with a magnetic field, by a factor which is equal to the number of times an electron revolves around the vehicle's dimension between collisions, squared, then you can, in fact, charge up the vehicle with a relatively small accelerator.

Q. *Would we have the opportunity to turn this device off now and again, for achieving docking maneuvers?*

A. Yes, it takes only twenty seconds to establish the field. Or you take a few minutes; that wouldn't be a problem.

Q. *Would it charge the ship up?*

A. I suspect there would be some sort of resistive divider between the ship and the central hub.

Q. *Would this field affect communications between Earth and the satellite?*

A. If it starts picking up its own Van Allen belt, there could be some interaction. But I don't think that's a problem, because we were able to reach the Apollo astronauts through the Van Allen belt.

Q. *Your shield focuses particles, primarily protons, and protons are hydrogen. Would it be of any advantage to use your field as a solar wind catcher?*

A. The solar wind flux is quite low, because the particles move at very slow velocities. You would need to sweep an area thousands and thousands of kilometers in diameter to scoop up an appreciable amount of hydrogen.