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Radiation shielding of spacecrafts in interplanetary flights

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Abstract

During the interplanetary flights the crew members will be exposed to cosmic ray radiation, with great risk for their health. The absorbed dose due to CR depends on the galactic (GCR) or solar (SCR) origin. GCRs are isotropic, and relatively high in energy and deliver a dose nearly constant, with the time, that can be reduced only by means of ”heavy” passive protections. The SCRs up to a few tens of MeV are usually shielded by the outer walls of the spacecraft, but during some exceptional solar bursts, a great number of particles, mainly protons, are ejected at higher energies. In this case the dose given in a few hours by a solar burst can easily exceed 1 year cumulated dose by GCRs.The high energy component of SCRs is quasi-directional so that a shielding system based on a superconductive magnetic lens can reduce the daily dose of SCRs to the only one delivered by GCRs.

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1 Introduction

The magnetic field of the Earth protects life from external sources of radiation. On the equator line a proton can reach the Earth surface only if its momentum is higher than about 15 GeV/c. At higher latitudes, even though the protection is much weaker, the magnetic field still prevents from the arrival of the low energy particles ($E_k < 100$ MeV), which constitute the most relevant part during the maximum of the solar activity. In future manned interplanetary missions the human crew will be no longer protected by the Earth magnetic field, and therefore exposed for long time, up to a few years, to the solar and galactic radiation. Both these components are dominated by protons, all the rest amounting to no more than 10 % of the total at the same E_k/nucleon. The flux of the galactic protons has its maximum at about 1 GeV, and it is still abundant beyond several tens of GeV, while the solar protons can be abundant at E_k below a few hundreds MeV (Fig. 1).

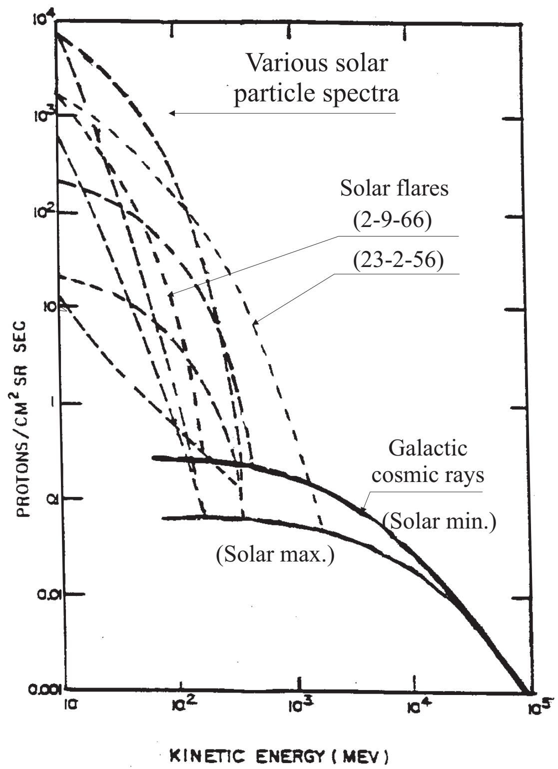

Figure 1: Solar and cosmic protons spectra.

The intensity of proton bursts, produced by violent events on the solar surface and in the solar corona (solar flares), are irregular and unpredictable, with dramatic spikes in correspondence to the largest solar flares. In average its integral on many days periods varies by more than one order of magnitude during the eleven years of solar cycle.

The trajectories of the solar cosmic rays follow the magnetic field lines generated by the "solar wind". The magnetic field due to this wind prevents the penetration of the galactic cosmic rays in the inner region of the solar system. Therefore the galactic cosmic rays are anticorrelated with the intensity of the solar activity.

The protection from the galactic component of the human crew in the interplanetary space looks very difficult, both for the high energy of the particles and for their isotropy. A substantial reduction by total absorption should require several tens of cm of equivalent aluminium absorber all around the spacecraft (see table 1), or at least all around the volume where the astronauts spend most of their time during the flight. However, the effects of the galactic component on the human body are smaller than those of the solar one, because of the high energy of its main component (protons), that behaves in the materials as a flux of minimum ionizing particles (mip), releasing only few tens MeV/proton in the astronaut body. The total dose due to the hard part ($E_k > 0.5$ GeV) of the GCR, cumulated in one year by the astronauts at the Earth orbit, ranges from 2.5 to 4 cSv depending upon the solar activity [1].

The solar cosmic rays are potentially more dangerous than the galactic ones, for their spikes in intensity and because they release all the energy in the absorbing body, with the highest release in a very small volume at the end of their paths, where they can cause severe biological damages. However two important features of the solar protons may help to plan a defence against them:

(a) the bulk of their flux is relatively soft in energy;

(b) the most penetrating ones run along a preferred direction.

The soft component of the solar proton spectrum can be greatly reduced before reaching the astronauts by total absorption [2] in relatively thin absorber's (table I).

In order to shelter the astronauts from the hard part of the solar proton spectrum, one can take advantage of their directionality, by shielding the spacecraft only on the side of their incoming direction. Since most harmful incoming particles have positive charge the passive absorber protection can be complemented by an active protection based on a magnetic lens deviating them.

In the following, after a brief discussion of the "quasi-beam" behaviour of the most energetic solar cosmic rays (section 2) and the effectiveness of the passive protection made up by the mechanical structures of the spacecraft (section 3), it will be evaluated the complexity of an active protection based on a magnetic lens produced by a system

Table 1: Protons range in aluminium.

$Energy(Mev)$	$Range(g/cm^2)$
$1 \times 10^{+4}$	$5.76 \times 10^{+3}$
$5 \times 10^{+3}$	$2.85 \times 10^{+3}$
$2 \times 10^{+3}$	$1.02 \times 10^{+3}$
$1 \times 10^{+3}$	$4.12 \times 10^{+2}$
$5 \times 10^{+2}$	$1.49 \times 10^{+2}$
$2 \times 10^{+2}$	$3.33 \times 10^{+1}$
$1 \times 10^{+2}$	$1.00 \times 10^{+1}$
$5 \times 10^{+1}$	$2.93 \times 10^{+0}$
$2 \times 10^{+1}$	5.75×10^{-1}

of superconducting coils. In section 4, the evaluation is made for a directional magnetic shield, protecting only from the particles coming from one direction.

In the evaluations we take in consideration only the proton component of the radiation. In fact, the electron component has a much lower kinetic energy and can be indeed easily absorbed. The nuclei are potentially more dangerous than the protons, but are much less abundant at the same kinetic energy per nucleon and treated in the same way as the protons by the active system (with the obvious Z/A scaling). The electron component has an abundant relativistic tail travelling at the speed of the light and therefore the detection of this component could play an important role in the case of powerful solar flares to "alarm" the spacecraft on the arrival of the shortly following protons. The results of the evaluations for the active protection are compared to the mass of an equivalent passive system based on total absorption in aluminium (section 5). Finally in section 6 it will be discussed the effectiveness of these systems in relation to the protection of the health of the astronauts.

2 Are the high energy solar cosmic rays directional?

Most of the particles of solar cosmic rays have a so small energy that they can be stopped by a thin layer of material, 2-3 mm of Al equivalent. This can be considered the minimum thickness of a whatever external wall of a spacecraft that must support the pressurization of the inner volume of the spacecraft. Therefore for the protection of the astronauts inside a spacecraft we are concerned with proton kinetic energies ranging from 30 MeV up to a few hundreds of MeV (see Fig. 1). The solar cosmic rays travel from the Sun to the Earth orbit, at 1 AU, rolling up around the solar magnetic field lines. In order to evaluate the dispersion of the direction of the particles around their guiding field lines, it is necessary to discuss and understand the shape of these lines in the interplanetary space [4].

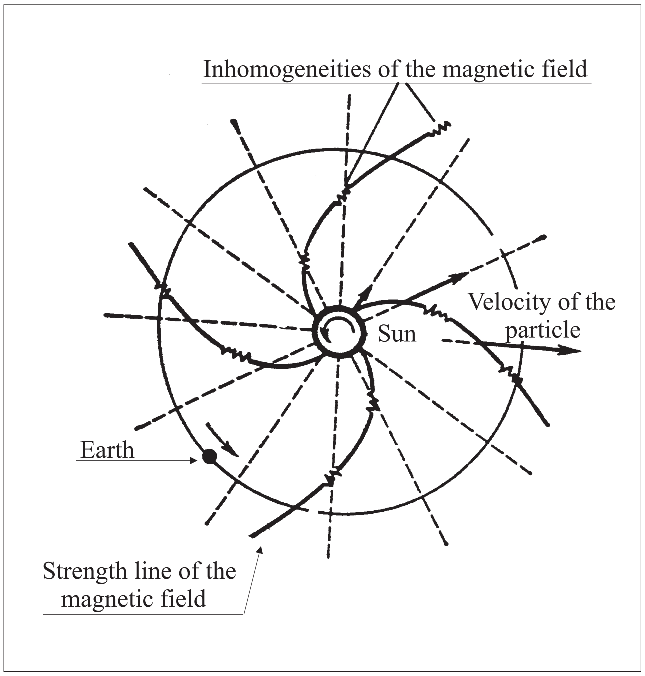

Figure 2: Solar magnetic field.

The shape of the field lines is determined by the outflow of charged particles from the Sun, the so called 'solar wind'. In first approximation these particles constitute a collisionless plasma with infinite conductivity. Therefore the plasma and the magnetic field are strongly tied together, as if the field lines were 'frozen' in the plasma (flux freezing phenomenon).

The solar wind is radially released with a nearly constant speed of about 700 km/s in the solar polar regions. In the region up to about $\pm 20° \div 30°$ from the eclictic plane the solar wind is much slower with an average speed of 400 km/s and a total dispersion of about $\pm$200 km/s. It is difficult to image the need of an interplanetary flight traveling far away from the eclictic plane, so that only the characteristics of the solar wind around the eclictic plane will be considered. In the eclictic plane, the stream of the radially moving particles originated from one point of the solar surface around the solar equator, traces out an Archimedian spiral (similar to the water stream of a rotating garden sprinkler) due to the 26 days rotation of the Sun around its axis. During the several days that the wind needs to reach the Earth orbit, the Sun surface rotates of about 60 degrees so that the stream crosses the Earth orbit forming an angle of about 45 degrees with the Sun-Earth radius. The lines of the magnetic field follow the stream of the particles, and they have their same shape, linking by the Archimedian spiral each point of the interplanetary space to the point on the Sun surface from where the stream of the particles was originated (see Fig. 2). The spread of the solar wind velocities determines a spread of the shape of the spirals. For the two velocity extremes, 200 and 600 km/s, we have the situation sketched in Fig. 3, with the stream of particles reaching the Earth orbit forming an angle with the Sun-Earth radius ranging from 30 to 50 degrees.

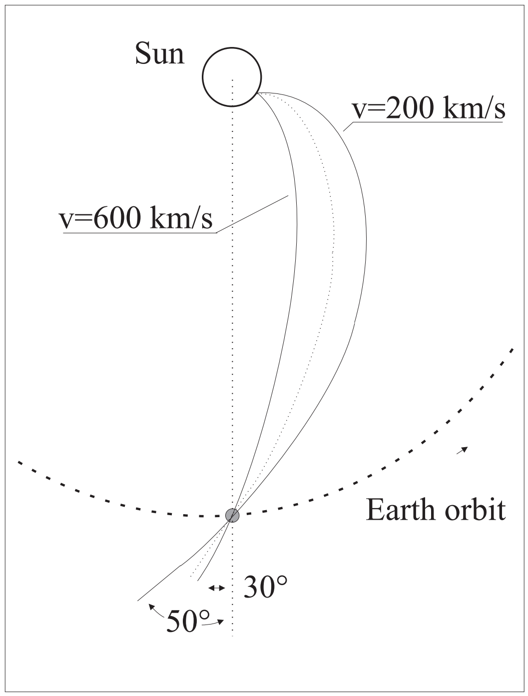

Figure 3: Angular spread of the solar wind direction at earth orbit.

This pattern of the solar magnetic field prevents the less energetic galactic cosmic rays to reach the inner part of the solar system. In fact, as they approach the Sun, they are reflected back by the "magnetic bottle" effect due to the increasing intensity of the solar magnetic field. Local inhomogeneities scattering galactic cosmic rays are superimposed to this underlying structure of the field. They become more important during the periods of more intense solar activity, and are responsible for the variable cycle of the galactic cosmic ray flux. In rolling up around the magnetic field lines the solar cosmic rays progressively align with them due to the decreasing of the field intensity (focussed transport, see Fig. 4). This behaviour is perturbed by the scattering of the particles on the inhomogeneities of the field, which tend to randomize their direction. Even though this effect is rapidly decreasing with the increase of the particle energy, it still gives an angular dispersion of several tens of degrees at a few MeV. Therefore the total angular dispersion of the solar cosmic rays in the interplanetary space is the convolution of their dispersion around the guiding field line and the dispersion of the field line directions due to the velocities spread of the "parent" solar wind.

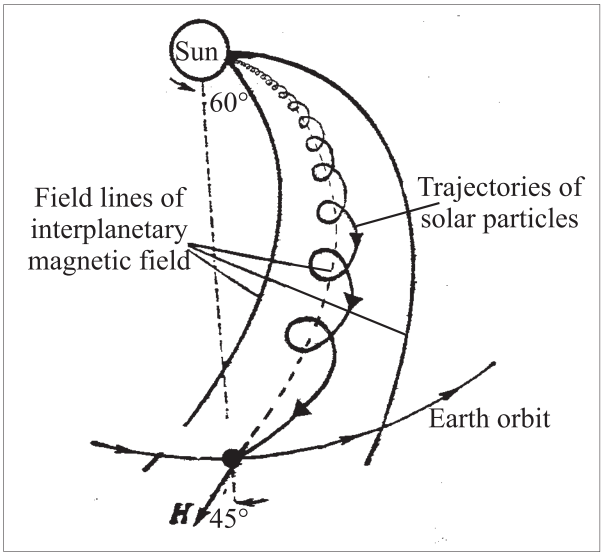

Figure 4: Trajectories of protons.

This summary description concerns the greater part of the solar cosmic rays, those accelerated by localized and fast solar flares on the Sun surface. The real situation, obviously, is more complex. First of all, it happens that some of the magnetic field lines starting from the solar surface are closed on the sun itself. The solar cosmic rays are trapped in a kind of magnetic bottle and oscillate between the two mirror point of the bottle. There are therefore geometrical situations where at the Earth orbit the flux of the solar cosmic rays tends to be isotropic, and the particles can also arrive from two opposite directions. In the events of this category reported in the scientific literature the particles have relatively low energy, with relevant fluxes only up to a few MeV of E_k: they should not substantially contribute to the radiation exposure inside the shell of a spacecraft. The same should be true for the solar cosmic rays accelerated in "collective mode" by an interplanetary shock wave, expanding from the Sun. At a large distance from the Sun, instead of the short duration peak in the intensity peculiar of the fast solar flares, it is observed a slow increase (during several days) of the flux, followed by an equally slow decrease. The angular distribution of these cosmic rays is nearly isotropic and the global intensity not negligible when compared to the global intensity due to the solar cosmic rays accelerated in the fast solar flares. However, also this mechanism mainly concerns solar cosmic rays whose E_k is too low to reach the astronauts inside a spacecraft. Therefore, in the following of our discussion it will be considered only those solar cosmic rays accelerated by fast solar flares events occurring in regions of the Sun surface magnetically well connected to a given position in the interplanetary space.

In the scientific literature the angular dispersion of the solar cosmic rays is reported as an 'asymmetry' parameter, that is a parameter given by the integral of the angular distributions in two opposite hemispheres. Only for a few events a very coarse angular distribution is reported, integrated in very wide sectors. From these informations it can be deduced that the dispersion of particles of a few MeV of E_k is confined in $\pm$ 30 degrees around the guiding magnetic field line, but the information is not enough for reconstructing the angular distribution inside this large angular sector. However it is reasonable to assume that at the energies of our interest the angular distribution should be narrower, probably only a few degrees at more than 100 MeV, and the angular dispersion of the magnetic field line distribution should prevail in the global angular dispersion [3].

This situation offers a noticeable advantage in handling the problem of the radiation protection: the direction of the field lines can be foreseen well in advance, either by monitoring the activity of the Sun or by magnetometer's installed on the spacecraft itself, or also by magnetometer's located in suitable regions of the interplanetary space. In any case the direction variations of the magnetic field lines could be computed on the basis of the existing vast catalog of data on the Sun behaviour. It could be also worthwhile to send a small interplanetary sonde through the same region foreseen to be crossed by a subsequent manned spacecraft, either for checking the computed previsions or for acquiring a more detailed and appropriate information on the directions of the particles as a function of their energy. The present very precise tracking techniques allow to conceive an accurate magnetic spectrometer of a few kg of mass that could gather all the needed informations up to several GeV of E_k. In conclusion we can say that a system of protection from the effects of the solar cosmic rays must profit of the marked directionality of the particles accelerated in the same solar events, and possibly include the capability to be rotated to allow the best alignment with the local magnetic field. It could also include, besides a system of magnetometer's for the instantaneous measurement of the direction of the local magnetic field, also a detection system for e^- particle flux which preceed of several minutes the arrival of the fast proton component.

3 The passive protection

The first protection is constituted by the mechanical structure of the spacecraft. This in general will be very effective for cosmic rays with no more than about 30 MeV/nucleon of E_k. For example, the averaged thickness on the MIR space station is 1 g/cm^2 of equivalent aluminium, reaching 7 g/cm^2 only in particular places inside the spacecraft. For a more generalized example, let us consider a spacecraft whose external dimensions match the Shuttle capability, i.e. with a radius of 2 m and several meters in length. Its external vessel should have a mass of 1020 kg for each 3 mm of 'equivalent aluminium' and each 10 m in length. This thickness of aluminium can stop, by ionization losses, all protons with less than 25 MeV of E_k. Adding a further absorbing material around a more restricted volume, where the astronauts are supposed to spend most of their time, would result in further heavy mass to be added to the spacecraft. The protection of a section of our hypothetical cylindrical spacecraft, 1.5 m in radius and 3 m long, require 115 kg for each mm of aluminium, i.e. 3450 kg for stopping protons up to 100 MeV. We could do better by concentrating the absorber around a smaller volume, where the astronauts could shelter in case of 'radiation alarm'. The mass of aluminium around a cylindrical volume 0.5 m in radius and 2 m long would be 12 kg for each mm of thickness, i.e. 360 kg for stopping protons up to 100 MeV, which rises up to 1160 kg for stopping protons up to 200 MeV.

4 A magnetic lens for shielding the spacecraft from the solar part of the cosmic ray radiation

The good directionality of the solar cosmic rays allows to conceive a cylindrical magnetic lens for defocussing all the positively charged particles away from the axis of the lens. The need to minimize the mass does not leave any choice for the technique to be used for the magnetic field production: it must be realized by superconducting coils, and without the use of iron jokes. This implies a refrigeration system to keep the superconductor at the low temperature necessary for its operation. For what concerns the techniques that can be envisaged for the coil in more than ten years from now, it is probable that the NbTi material presently used for the industrially produced superconducting cables could be substituted by the Nb_3Sn material that is already used in magnets for high field spectroscopy and, since few years is also used by industry for construction of large coils (for fusion researches and for specialised projects). The use of Nb_3Sn material will certainly reduce the mass of the superconductor material needed for the coils, increasing both the intensity of the field that could be produced, and the operating temperature, increasing also the stability limits. Actually, beyond NbTi and Nb_3Sn, one can envisage the use of ceramic high Tc superconductors (HTS), like Ag stabilised Bi-2223 tapes; in fact within 2 or 3 years the effectiveness of such a material in real size coils may be proved by industry for big projects (SMES and other electric applications).

The fast progress of cryogenerators for space and other applications allows to reasonably envisage that in the future their reliability, mass and power consumption will match the request for their use in interplanetary flights, thus reducing drastically the volume and mass of the helium supply. Surely it should be much better to use cryorefrigerating systems capable of maintaining the temperature of the coils at a few kelvins without requiring at all liquid helium. Presently the needed mass need and the power consumption rule out this solution. However also for this kind of device the technical progress promises to be quick, and a suitable R&D activity devoted to their use in long duration space flights could bring their parameters in the useful range.

In the following the evaluation for the magnetic system will be based on the use of NbTi superconducting material whose performances are well known expecially for the intensity of the field and the needed refrigeration power. No specific hypotheses will be done for the cooling system at this stage of the discussion. A magnetic lens can be obtained by a toroidal configuration: an electrical current running along a cylindrical conductor, parallel to its axis, with the electric current circuit closed in a return circuit. The simplest scheme for the return circuit consists of a cylindrical conductor at a larger radius carrying the return current, connected by radial conductors to the inner cylinder.

Because at this stage is not worthwhile to go in detail for the geometry of the lens, we will assume that the innermost and outermost cylinders, as well as the connecting radial connectors, are continuous surfaces, and the total cross section of the conductor is constant along the whole circuit. The diameter of the inner cylinder is assumed to be 0.5 m and its length 1 m. The radius of the external cylinder can be as large as we wish, since its mass does not change with the radius, and only the mass of the connecting radial connectors changes. However, since the magnetic lens must be transported to space already assembled, its external diameter cannot exceed that of a big rocket or that of cargo bay of the shuttle vehicle (the diameter of cargo bay of the nowadays shuttles is 4.6 m). We will assume 4 m for the external diameter of the lens, and we will maintain the length of 1 m also outside (see Fig. 5).

The region inside the inner cylinder could be well protected against the incoming radiation by the mass of the technical devices servicing the coil, adding a further absorber only in the parts not well protected by them. For an approximate evaluation, let us assume that we deviate of 45 degrees the cosmic rays arriving parallel to the axis of the coil at a radius slightly exceeding 0.25 m. For 500 MeV kinetic energy protons is then required sligthly less than 3 $T\times m$ of integrated field.

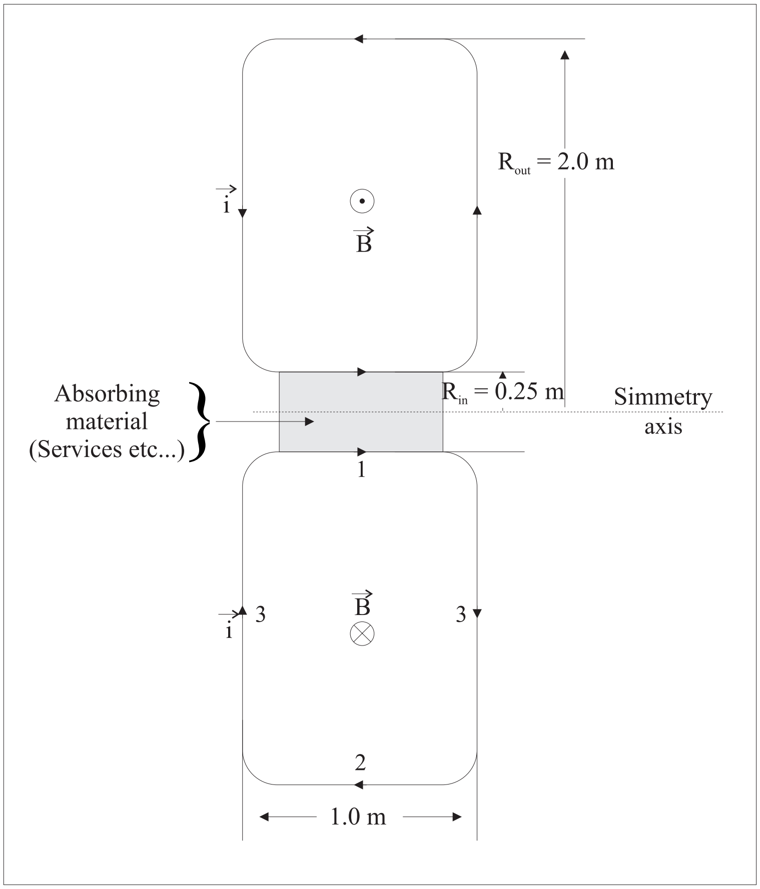

Figure 5: Longitudinal cross sectional view of the toroidal coil configuration of the magnetic lens. 1) Inner cylindrical conductor. 2) Outer cylindrical conductor. 3) Radial connectors.

The total current to obtain such a field is about 3.5 MA. We assume to have a current density of 3,500 A/mm^2 in the inner cylindrical conductor, which is a safe working point for a NbTi superconductor [1] This choice brings to an average current density of 700 A/mm^2 flowing in the whole coil. Hence the mean cross section of the s.c. coil turns out to be 50 cm^2, accounting for a total volume of the s.c. of 50 cm^2 x 560 cm = 27840 cm^3 and a mass of 103 kg. The average thickness of the s.c. in the inner cylinder is 3.2 mm and in the outer one is 0.4 mm. With this coil the resulting trajectories of 500 MeV protons arriving at some selected distances from the axis of the lens are reported in Fig. 6. A glance to this sketch of trajectories indicates that the deflection power of the lens

[1] The industrial production of NbTi superconducting wires is already at a critical current density of J_c = 5000 A/mm^2 at B=2.8 T and 4.2 K, so we consider to work at 70 % of the critical current.

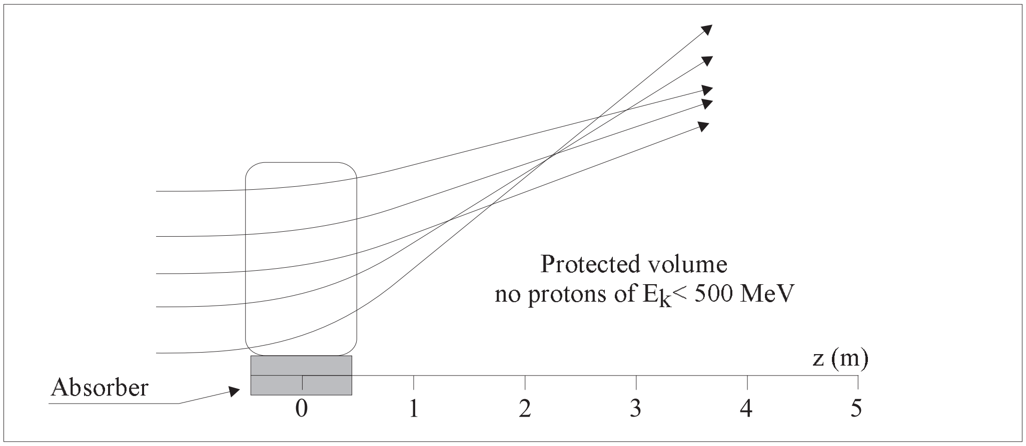

Figure 6: Deflected trajectories of the protons and the protected volume.

should be reinforced around 1m of radius in order to maximize the volume of the fully protected part of the spacecraft.

This maximization can be obtained by a circular shaped coil. Such a choice represents also a better geometrical situation for the mechanical structure that should support the magnetic stresses produced by the high field inside the lens. With this choice for the shape of the coil and assuming the same parameters as before, with the same maximum field at R=0.25 m, the trajectories of 500 MeV protons are those sketched in Fig 7. The fully protected volume significantly increases in comparison to the case of the rectangular shaped coil of Fig. 7. Furthermore, if the coil could be realized by a nearly continuous surface, the coil could be nearly self-supporting against the magnetic stresses, in spite of its thin average thickness: in fact the magnetic stresses are directed outside the volume of the coil and nearly perpendicular to the conductor, and their effect is equivalent to a buckling pressure that probably requires only relatively light external structures. Therefore the total mass of the magnetic lens will require the addition of the only masses of the thermal shields and of the cooling system.

An other important advantage of constructing a nearly continuous surface coil is that the magnetic field will be fully contained inside the volume of the coil, with no external fringing field.

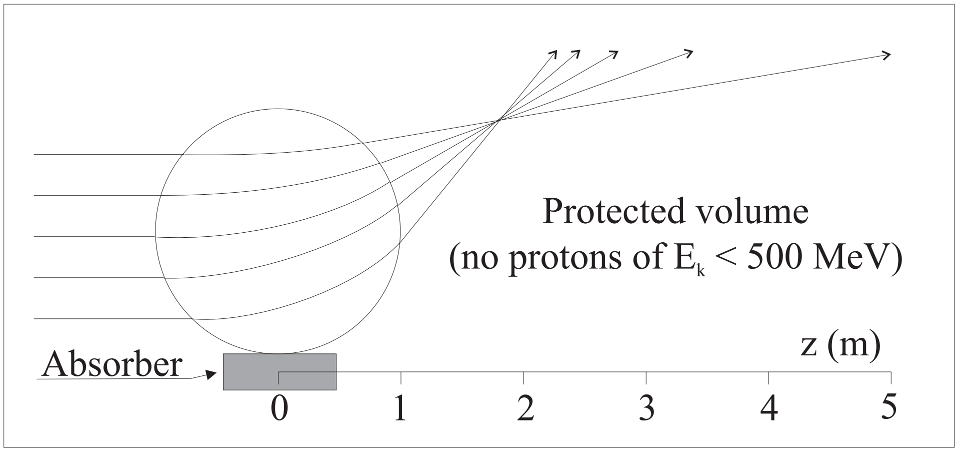

Figure 7: Circular shaped coil: B_{max} = 2.8 T, I_t = 3.5 MA, mass = 105 kg.

5 Comparative discussion of passive and active protection from the cosmic ray radiation

Let begin comparing the mass of the magnetic system based on the circularly shaped coil of Fig. 8 with the mass of the absorber needed to have the same protection. Also the absorber can profit of the directionality of the arriving cosmic rays, and to consist therefore of a disk of the same diameter of the external diameter of the coil. The internal part of the disk (up to 0.25 m in radius) is common to the two devices and must be kept out from the comparison. The surface of the disk will be indeed 12.5 m^2. The total mass of the magnetic lens has to be evaluated adding to the mass of the coil the masses of the thermal shields, of the cooling system and of the supporting structures. In first approximation these masses can be considered proportional to the mass of the coil itself. The proportionality factor is completely arbitrary without the consideration of a specific design, and it will be considered arbitrarily equal [2] to 1. However it is reasonable to assume that all the elements servicing the coil cannot be lighter than some minimum mass, that will be arbitrarily [3] assumed to be 50 kg. The results of the comparison are reported in table 2 and in Fig. 8 for several values of the maximum kinetic energy of the particles.

It is clear that as we move up from the region of few tens MeV of the proton, the magnetic system is very convenient.

[2]This is a reasonable and conservative hypothesis by considering the use of light and strong Al alloys.
[3]Again, probably, technology improvements can lead to consider 25-30 kg as minimum fixed load.

Table 2: Comparison beetwen the directional magnetic lens and an equivalent Al absorber.

		magnetic lens						Absorber		
E_k MeV	p MeV/c	B_{max} T	Itot MA	I A mm^{-2}	mag. kg	sys. kg	tot kg	$\rho\times$L gm/cm^2	L cm	tot kg
40	277	0.70	0.87	1020	18	50	68	2	0.74	250
100	441	1.13	1.41	980	30	50	80	10	3.7	1250
150	551	1.40	1.74	950	38	50	88	16	5.9	2000
300	808	2.07	2.57	840	63	63	126	52	19.3	6500
500	1090	2.80	3.48	700	103	103	206	141	52.2	17625
1000	1696	4.36	5.41	560	200	200	400	376	139.3	47000

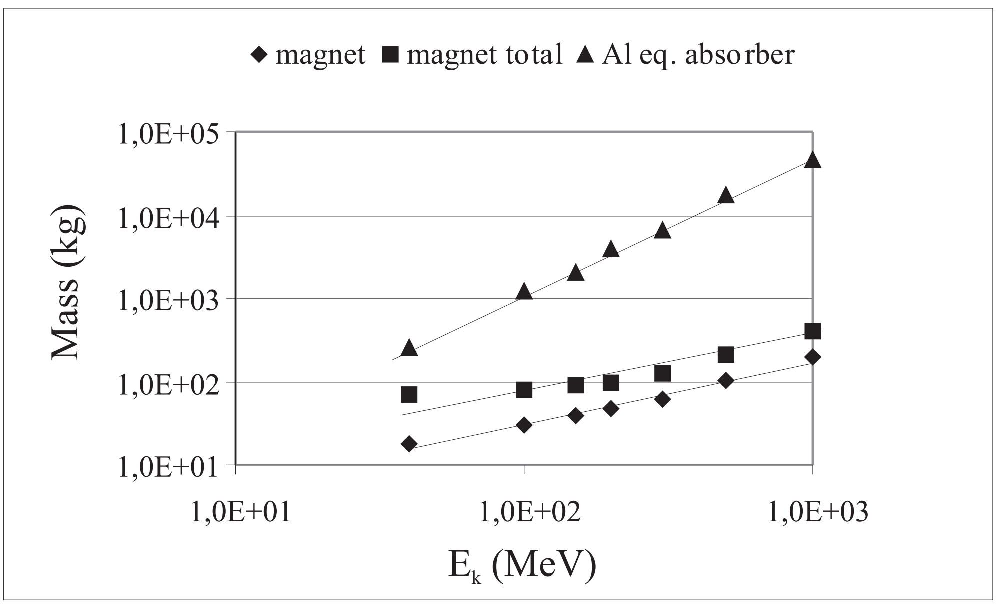

Figure 8: Weights of active and passive shield vs cutoff energy. Triangles: passive shield, diamonds: magnet mass of the active shield, squares: total mass of the active shield.

6 Effectiveness of the protection for the health of the astronauts

Cosmic radiation may have dramatic acute or tardive effects on the health of astronaut during long space mission. The damages depend on several aspects such as the kind, the quality factor and the intensities of the radiation, besides of the individual skilful at cellular reparations. We are interested in a quantitative evaluation of the contribution to the total dose given by various kind of radiation present in the interplanetary space. Among those we are particulrly interested in the evaluation of the absorbed dose delivered by galactic cosmic rays and by solar bursts.

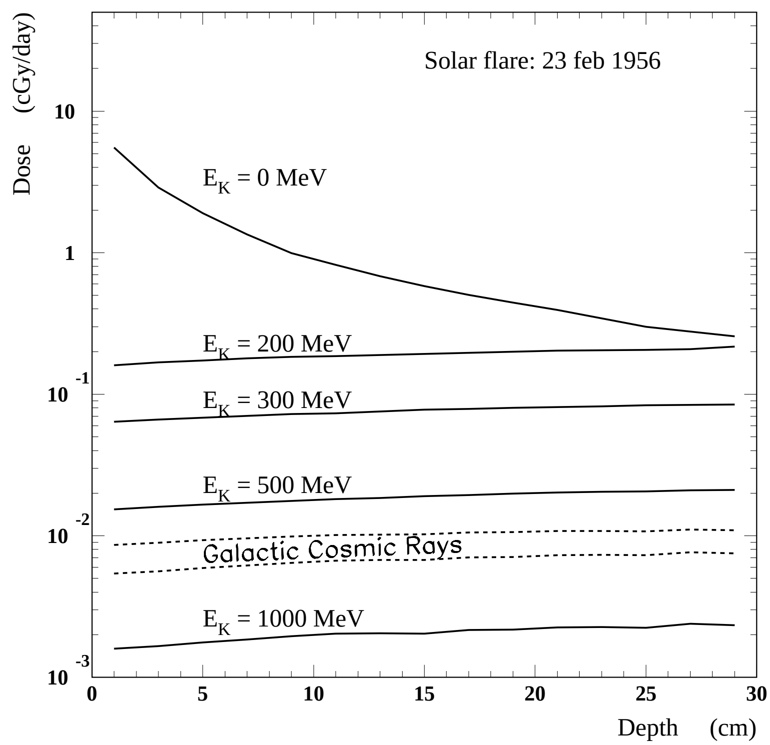

Figure 9: Dose delivered by GCRs (dashed lines) and by SCRs (solid lines) during the solar burst of February 1952, with and without protective shields as function of the depth in the body.

The evaluation of the mean absorbed dose by the astronauts was performed by means of Montecarlo simulation with the GEANT code. Different enviromental conditions were considered, taking particular care of the radiation quality and the used pro-

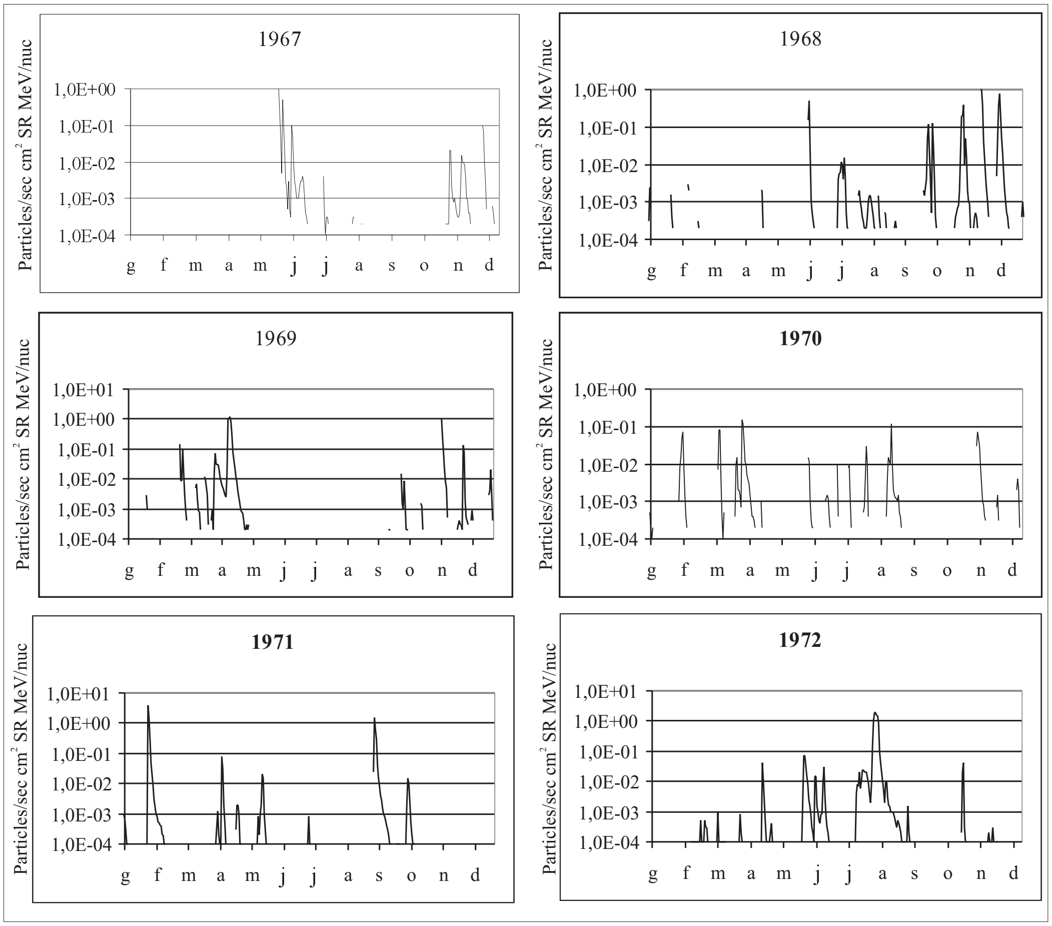

Figure 10: Monitored cosmic rays 1967-1972 by IMP IV and IMP V experiments. The differential fluxes are measured in the energy range between 20 and 80 MeV. In the same energy the galactic cosmic ray flux is less than 10^{-4} (cm^2 s sr MeV)$^{-1}$.

tecting magnetic field. In simulation the cutoff energy for particle tracking was set to 10 keV, a value for which the remaining energy of the particles can be supposed to be fully deposited 'in situ'. In the chosen geometrical conditions the direction of the incoming flux of proton is orthogonal to the spacecraft outer wall, 2.7 mm of Al, either for galactic cosmic rays or solar bursts. The dummy astronaut represented was by 60 layers, 5 mm thick, of water lies at a distance of 2 m from the wall and 1 m from the magnet. The inside environment of the spacecraft was filled with 1 atmosphere of nitrogen gas.

Since the GCRs are quite isotropic their contribution to the absorbed dose is to be considered unavoidable because it can be reduced only by means of "heavy" passive protections, such as the increasing of the spacecraft walls. The dose released by GCRs is continuous in time and well below the safety threshold accepted by the main space Agencies. On the other hand, during the solar flares, the SCRs can release in a few days a dose equal to that delivered by an exposition to GCRs of some years.

In Fig. 9 the daily dose released by GCRs is reported for the maximum and the minimum of the solar activity. In the same figure the dose delivered by a solar burst of the same characteristics as that of February 1952 is reported for different values of the energy cutoff. The effect of the active shielding is visible and the mean absorbed dose, that in absence of the active shielding results to be of about three order of magnitude greater, is reduced to the same amount of the one given by GCRs.

From the results of Fig. 9 two main considerations can be pointed out:

1. the necessary cut in E_k is about 500 MeV.

2. greater cuts seem not to be necessary also because (see Fig. 1) the burst of February 1956 was one of those with an exceptionally hard component.

To give an idea of the effect of SCRs on a period of several years, in Fig. 10 it is shown data collected, continuosly from May 1967 to December 1972, by IMP IV and IMP V satellites[6]. During the whole period of the experiment (1967 – 1972) 185 solar flare events were detected: an event was defined as an increase in the flux of 20 – 80 MeV protons which exceeds 10^{-4} Protons/(cm^2 s sr MeV) and lasts at least for more than 5 hours.

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