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Radiation shielding of astronauts in interplanetary flights: the CREAM surveyor to Mars and the magnetic lens system for a spaceship

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Abstract

The radiation absorbed by astronauts during interplanetary flights is mainly due to cosmic rays of solar origin (SCR). In the most powerful solar flares the dose absorbed in few hours can exceed that cumulated in one year of exposition to the galactic component of cosmic rays (GCR).

At energies above the minimum one needed to cross the walls of the spaceship there are extrapolations and guesses, but no data, on the angular distribution of SCR's, an information that is necessary for establishing whatever defence strategy. It was therefore proposed of sending to Mars a measurement device, that should continuosly collect data during the travel, and possibly also in the orbit around Mars and on the Mars surface.

The device should identify the particle and privilege the completeness in the measurement of its parameters. In fact the high energy electrons travel at speed of the light and could be used in the and future dangerous proton component. Also the much less abundant but individually more dangerous ions should be identified. The device should indeed include a magnetic spectrometer and a high granularity range telescope, and a good time of flight measurement.

ASI is supporting an assessment study of a possible mission of such a device on board of the 2005 probe to Mars.

A parallel technical study is also in progress to define the workable techniques and the possible configurations of a system of magnetic lenses for protecting the crew of a spaceship.

KEYWORDS: Radioprotection, space, cosmic rays, superconducting magnets.

1. Introduction

In this report the discussion of the protection of the astronauts from the ionizing radiation will be confined to the interplanetary space far away from the effect of the terrestrial magnetic field, and therefore will not concern Earth's radiation belts.

Far away from the protection of the terrestrial magnetic fields, a spaceship is exposed and for a long period of time to the whole spectrum of the cosmic ionizing radiation, which is nearly totally due to charged particles: electrons, protons and nuclei. They are of galactic or solar origin. The former (GCRs) have higher energies (for protons, the flux has its peak at 1 GeV) but a lower flux, while the latter (Solar Energetic Particles, SEPs) have lower energies but a much higher flux [1, 2].

The high flux of the SEPs is mostly due to solar flares generated on the Sun surface and Coronal Mass Ejection (CME) events developing in the Sun corona.

The SEP flux is anything but constant in time. In correspondence of the most violent events it can increase in a time, that can be as short as a fraction of an hour, by huge factors, up to 10^6 over the flux of the GCRs in the same energy region [3], and last several days. These events are mostly constituted by energetic protons. They are very frequent, 30/year in average, sudden, and can be very fast (the proton flux component reaches its maximum at the Earth distance in a few tens minutes), last hours or days, and their occurrence is unpredictable. The fluence of the high energy SEPs overcomes by two order of magnitude the total fluence of GCRs.

Therefore in the following, without forgetting the final goal of an adequate protection of the crew from the whole spectrum of the ionizing radiation, the discussion will mainly concern the protection from the SEP protons, not only because it is easier, but also because is much more crucial as it concerns not only the health, but the life itself of the crew during the mission.

In fact the probability of SEP events as a function of their total fluence follows a log–normal probability distribution [4]. It implies a not negligible possibility of extremely strong events, delivering to the astronauts lethal doses in a very short time.

2. Characteristics of the SEP component of CR

Unlikely GCRs, the SEP spatial distribution is far from being isotropic.

Higher energy SEPs accelerated in solar phenomena have a much lower energy density than the solar wind and are thus forced to spiral around the magnetic field lines it generates (Fig. 1). Their arrival direction is thus well defined at a given point of the interplanetary space; fluctuations due to the speed of the

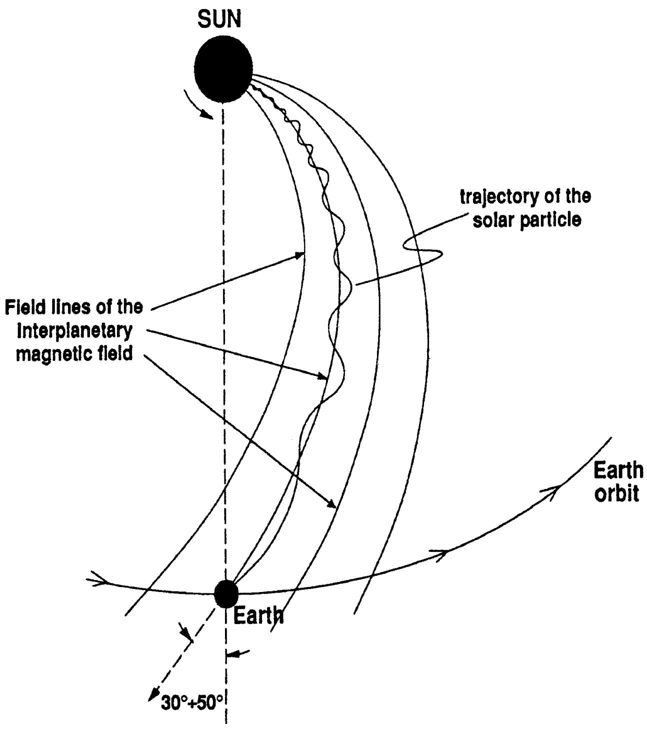

Fig. 1 – The energetic solar cosmic rays winding themselves around the lines of the magnetic field.

solar wind or other slow perturbations are typically of the order of a few tens degrees, and last a few hours or days. They can in any case be measured by the monitoring network of probes and satellites.

In addition to their acceleration in solar flares, however, SEPs are also produced in coronal mass ejection (CME) events as well. Radio observations, flux measurements in different points of the heliosphere, helium isotopic ratios have all pointed toward a more complex understanding of the possible mechanisms for the production and acceleration of particles of solar origin. In case of CMEs the large emissions of coronal material drastically changes the magnetic field line configuration and the deviation from the spiral structure can be very large [3].

3. The fundamental role of the angular distribution of the SEPs in the shielding design

If the angular distribution could be known in each situation, a shielding action could be obtained both by steering the spaceship in order to maximize the passive material interposed, and by active systems, based on the use of magnetic fields for deviating the incoming particles [5] (Fig. 2). In fact a protection system solely obtained by absorbtion of the ionizing radiation cannot be proposed because of the huge mass of the needed absorbers. It must be provided an 'active' protection, by deflecting the particles outside of the volume to be protected by means of intense magnetic fields.

In the design of this active protection the degree of directionality of the incoming particles plays a fundamental role. The angular distribution should be known with a precision of a few degrees in the energy range between a few tens MeV up to a few hundreds MeV. In addition a study of the temporal dependence of the flux of cosmic rays, both secular (related to the 11 year solar cycle) and short term (due to solar activity) is necessary to provide us a complete picture and helps in constructing a forecasting receipt.

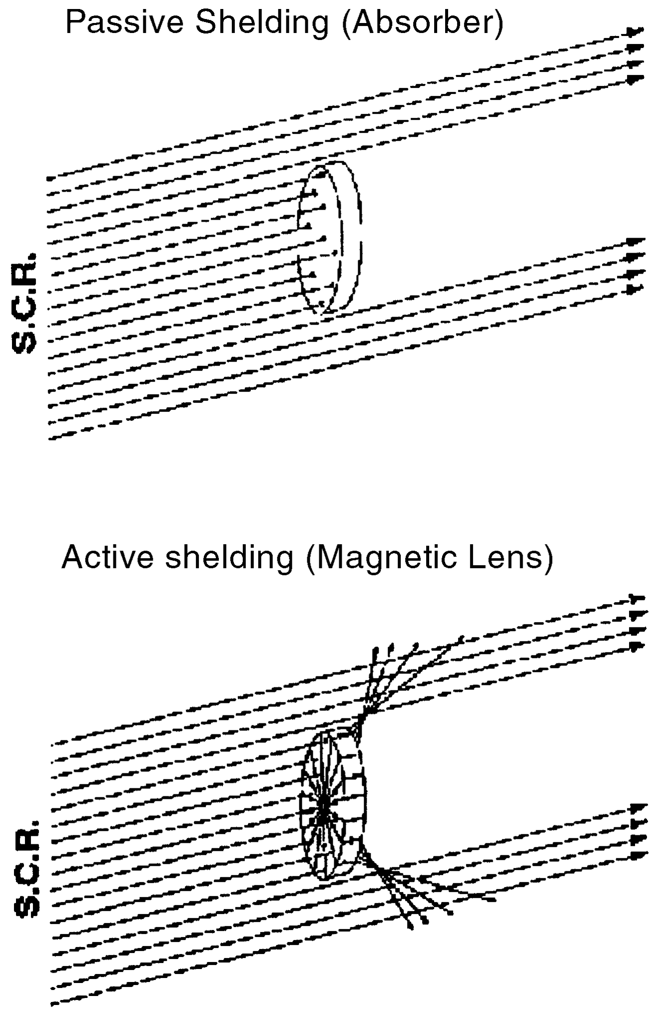

Fig. 2 – A defocussing magnetic lens can play the same role than an absorber in protecting a volume from the directional component of the solar energetic particles.

4. Search for angular distribution information on the record of the detectors on board of the interplanetary probes.

In order to gather information on the data availability of the angular distribution of cosmic rays in the interplanetary space in the interesting range of energy, we searched the record of the detectors on board of the spacecraft's sent outside the Earth's magnetosphere.

Out of the many probes sent by NASA, ESA, Soviet and Russian institutions and other agencies

[6] about 60 of them have on board instruments that are potentially of some interest for this search.

As a provisional conclusion we can affirm that a sufficient understanding of the angular distribution of the SEPs produced in the solar events can hardly be deduced either from the published data or from the data collected by the presently working probes.

5. A dedicated instrument to measure the SEP's angular distribution

Only flights in the interplanetary space of dedicated instruments can gather the important information of SEP angular distributions. Such instruments must measure the fluxes, angular distributions and nature of SEPs, as a function of time and of the position on the ecliptic plane. The simultaneous measurement of all these parameters is needed for understanding their correlation with the solar flares, the CME events and other possible kinds of solar phenomena.

A device consisting of an accurate magnetic spectrometer and an imaging range telescope ("Cosmic Ray from Earth to Mars – CREAM – surveyor) is sketched in fig.3. It should be operated on board of an interplanetary probe and run for a sufficiently long time, possibly covering an entire solar cycle, in order to gather as much as possible complete information for elaborating a receipt for a reliable forecasting of possible future events.

It must be looked for a flight opportunity on the Earth to Mars trajectory, possibly with a long measurement period on the Mars surface or in orbit around Mars. It could be caught the occasion of one

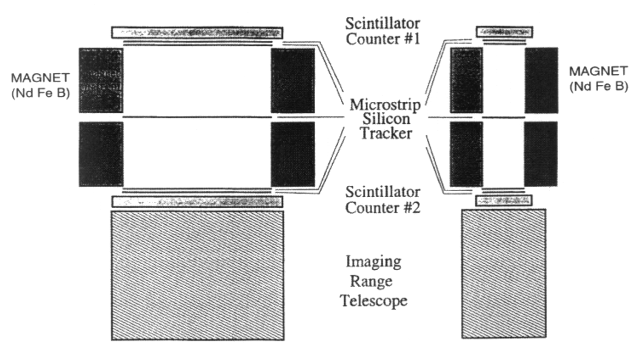

Fig. 3 – Conceptual scheme of the device for the CREAM (Cosmic Ray from Earth to Mars) surveyor proposed for identifying particles in the interplanetary space and to measure their energy and direction.

of the probes that are planned to be sent to Mars in the next future. Also if in this case the measurements will last not more than two years, there is the advantage of exploring the solar system region between 1 and 1.5 AU, where the first manned interplanetary flights are planned. A proposal of accommodation study for the MARS-2005 mission was selected last year by the Italian Space Agency.

6. Development of the techniques suitable for the operation of superconducting magnets in interplanetary flights

To protect crew members from the ionizing radiation, a magnetic system should highly reliably operate in the very hard conditions of an interplanetary mission, which will include the launch, the several months or years long flight, the orbiting around the visited planet, the possible landing and stay on its surface, and finally the return operations and return flight and the landing on the Earth surface.

The magnetic system must be based on superconducting coils, since other techniques result in massive and power consuming systems. Superconducting coils must be maintained at very low temperature, normally requiring large quantity of cryogenic fluids to be carried in space for servicing the coils. It must therefore be developed a system based on cryorefrigerators to avoid the use of large quantity of cryogenic fluids.

To afford this task a preliminary work has been performed, comparing the performance and operation stability of the different superconducting cables nowadays available. Numerical evaluations are conducted for a simple small solenoid carried out by different superconducting cables (Fig. 4) and compared for the same main parameters (mass and volume). The aim is to find the condition for operating a coil system based on the so-called High Temperature Superconductors (HTS) at low temperature, higher than the liquid helium temperature but such that it could be reached and maintained by low mass, low power consumption (avoiding cryogenic fluids for cooling the coils).

On the basis of the results of the work with the small coils, a prototype coil system of downsized dimensions (typically by a factor 5) will be realized to work for a long period of time in space, possibly on board of the ISS, where emergency operations would be possible. This reduced scale prototype is envisaged to be based on the use of HTS superconducting cables, directly cooled at about 20-30 K by cryorefrigerators in order to avoid the large scale use of cryogenic fluids. However the convenience of this approach should be validated by the computation and tests on the small solenoids above described.

7. Toward the project of a magnetic system for protecting the astronauts from the SEP

Preliminary evaluations for a magnetic system based on the well established technique of NbTi cables cooled by liquid helium indicates that a magnetic lens protecting a volume of several tens cubic meters by a quasi-directional flux of protons of energies up to 500 MeV is nowadays feasible. Not taking into account the liquid helium needed for operating the system for several years (about 500 kg/year), the magnetic system is much lighter than an equivalent passive absorber performing the same task (see

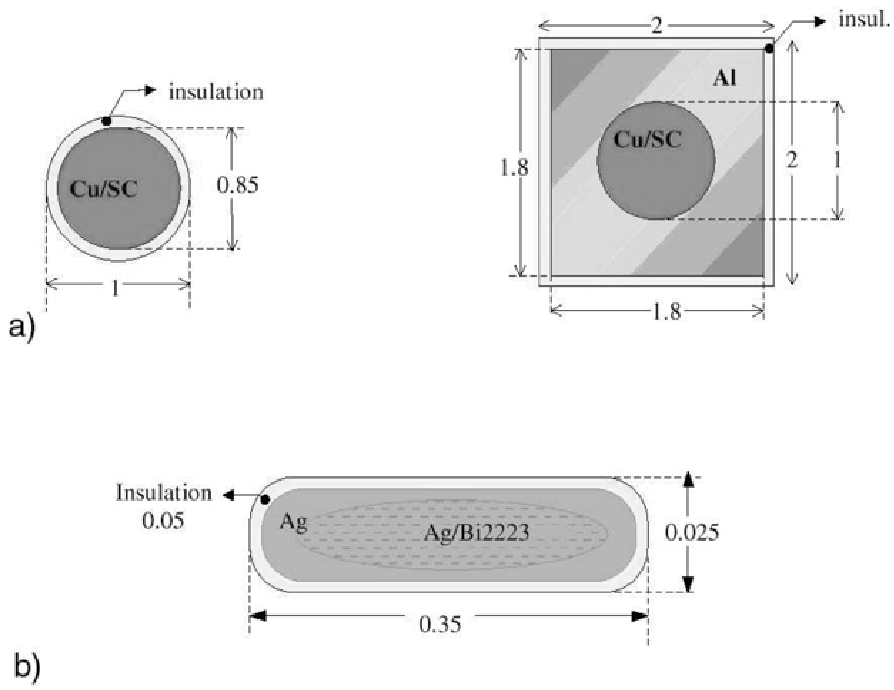

Fig. 4 – Cross section of the of the different superconducting cables used for the stability study of the small solenoid (all measures are in mm): (a) superconductors NbTi and Nb_3Sn, stabilized only with copper or stabilized also with aluminium; (b) HTS superconductor Bi2223.

Table I – Comparison between 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
5090	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

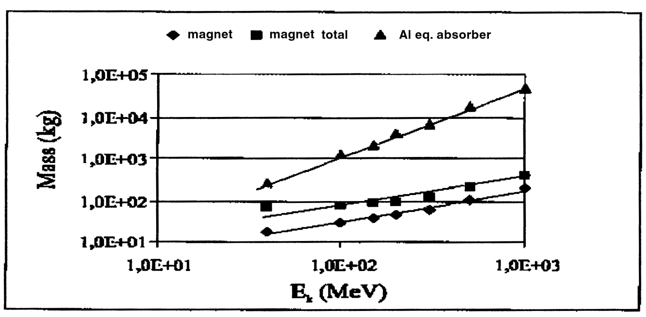

Fig. 5 – A magnetic lens of 2m radius based on a NbTi coil system cooled by liquid helium favourably compares with a passive absorber at all the ‘fully protected’ energies of the proton.

Table I and Figure 5). In the table and the figure the mass of the magnetic system is evaluated for different ‘full protection’ maximum energies, i.e. the energy below which the whole volume downstream of the lens is not accessible to protons.

The subsequent step of this activity will be the evaluation of the main characteristics and of the performance of a full scale scheme based on superconducting techniques not requiring the use of cryogenic fluids for cooling the coils.

The trajectories of 200 MeV protons arriving parallel to the symmetry axis and crossing a continuous toroidal lens designed for fully protecting the downstream volume from protons up to 200 MeV, are shown in Figure 6. The mass of this magnetic lens, evaluated for the different superconducting cables above considered for the small solenoid, is reported in Figure 7 as a function of the operation temperature. The Bi2223 cable gives the heaviest lens, but can be operated at higher temperatures, avoiding the use of liquid helium for its cooling. In any case these masses are much less than the 4 t of an aluminum absorber for protecting the downstream volume from protons up to 200 MeV.

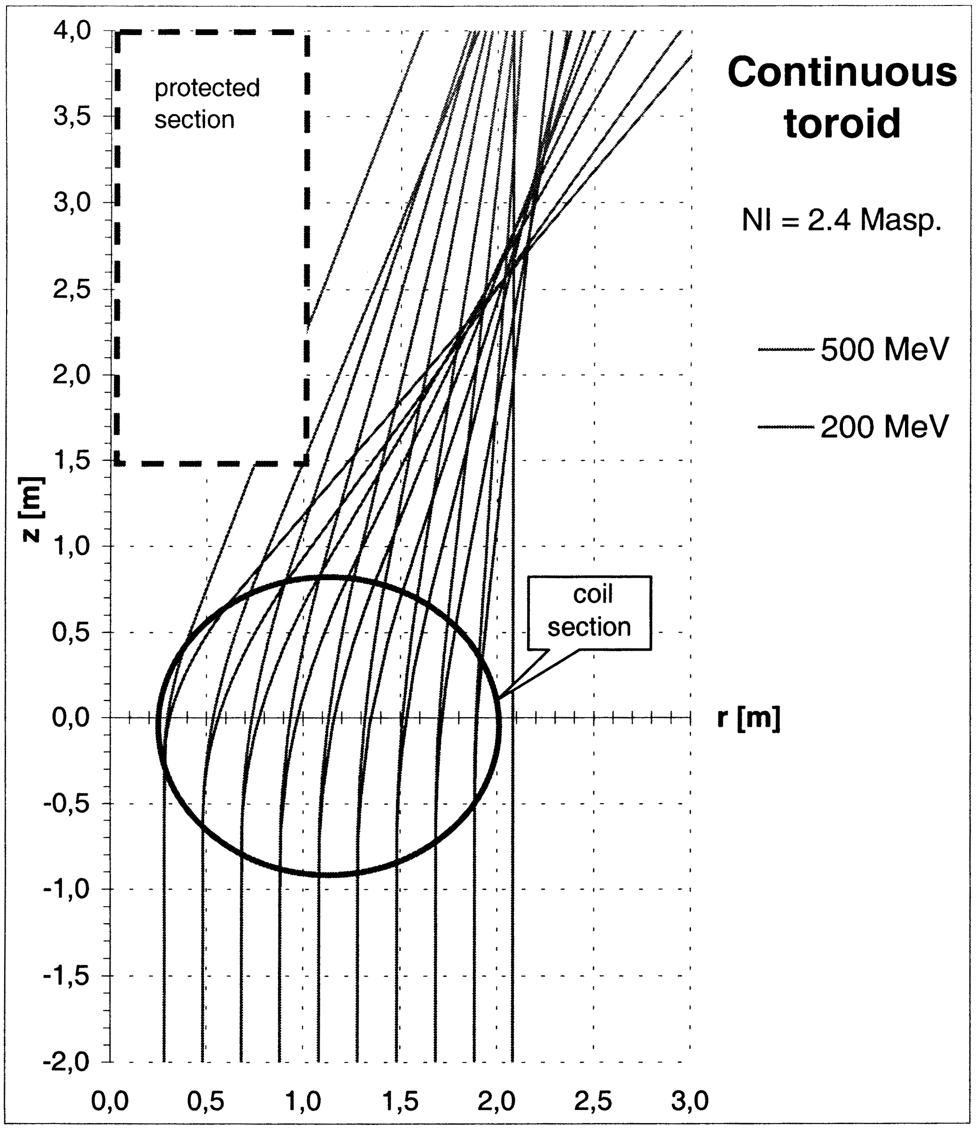

Fig. 6 – Trajectories of high energy protons coming parallel to the axis of a 'perfect' (i.e. with continuous external surface) toroidal lens of circular transverse section as a function of the distance from the axis of the lens. The toroidal lens is designed for protecting the whole volume downstream of the lens ('full protection') from protons up to 200 MeV. In the figure it is also shown that a volume of several cubic meters is protected from protons up to 500 MeV. It must be underlined that assuming a D shape for the transverse section of the coils improves the protection from protons with energies higher than 200 MeV.

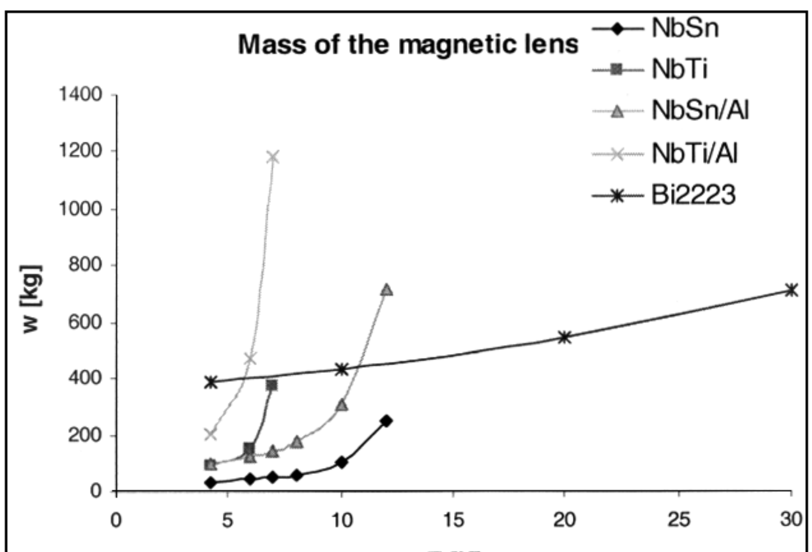

Figure 7 – Mass of the magnetic lens of Fig. 6 evaluated for the different superconducting cables considered for the small solenoid and as a function of the operating temperature.

8. Conclusions

In the previous sections the discussion is focused on the 'life-saving' systems, i.e. those protecting the astronauts from the lethal SEP.

Obviously on board of the spaceship also 'health-saving' systems should be foreseen, i.e. those systems that should protect the astronauts from most of the GCRs. At this stage of the discussion this task cannot be directly afforded, both for the lack of adequate techniques to produce extremely high magnetic fields in space and because of the nowadays limitations in mass and volume of the transportation systems and of the limited capabilities of assembling large systems in space. However this problem is strongly connected with that above discussed, and the solutions developed for the protection from the SEP could be a starting point for better defining the requirements for the protection from the GCRs and the appropriate R&D for affording the task.

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