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Manned exploration and exploitation of solar system: Passive and active shielding for protecting astronauts from ionizing radiation—A short overview

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A B S T R A C T

In deep space manned missions for the exploration and exploitation of celestial bodies of Solar System astronauts are not shielded by the terrestrial magnetic field and must be protected against the action of Solar Cosmic Rays (SCRs) and Galactic Cosmic Rays (GCRs). SCRs are sporadically emitted, and in very rare but possible events, their fluence can be so high to be lethal to a unprotected crew. Their relatively low energy allows us to conceive fully passive shields, also if active systems can somewhat reduce the needed mass penalty. GCRs continuously flow without intensity peaks, and are dangerous to the health and operability of the crew in long duration (> 1year) missions. Their very high energy excludes the possible use of passive systems, so that recourse must be made to electromagnetic fields for preventing ionizing particles to reach the habitat where astronauts spend most of their living and working time. A short overview is presented of the many ideas developed in last decades of last century; ideas are mainly based on very intense electrostatic shields, flowing plasma bubbles, or enormous superconducting coil systems for producing high magnetic fields. In the first decade of this century the problem began to be afforded in more realistic scenarios, taking into account the present and foreseeable possibilities of launchers (payload mass, diameter and length of the shroud of the rocket, etc.) and of assembling and/or inflating structures in space. Driving parameters are the volume of the habitat to be protected and the level of mitigation of the radiation dose to be guaranteed to the crew. Superconducting magnet systems based on multi-solenoid complexes or on one huge magnetic torus surrounding the habitat are being evaluated for defining the needed parameters: masses, mechanical structures for supporting the huge magnetic forces, needed equipments and safety systems. Technological tests are in preparation or planned for improving density of the current, lightness and stability, to increase working temperature of superconducting cables, and for finding light supporting structures and suitable safety architectures, delineating a possible development program for affording this difficult problem.

1. Introduction

In deep space, far away from the protection of the terrestrial magnetic field, the ionizing radiation is mainly composed of electrons, protons and ions accelerated to very high energy by Sun (Solar Cosmic Rays – SCRs) and by

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sources in the Galaxy (Galactic Cosmic Rays – GCRs) and in other galaxies. Gammas are much less dangerous to human health, and the effect of electrons can in first approximation be neglected.

SCRs are mainly composed of protons and are emitted and accelerated by Sun and its environment in short duration 'solar events' (Solar Particle Events – SPEs), lasting a few hours up to a few days. GCRs are much more energetic; their flux is continuous, varying by a factor ≈ 2 on the 11 years cycle of the solar activity. They are composed of protons (87%), helium nuclei (12%) and the rest by heavier nuclei such as iron, electrons and traces of trans-iron nuclei and antiparticles. In spite of the high abundance, the hazard to the human health given by protons is only about 1/5 of the total hazard constituted by GCRs because of the much higher ionizing power of the heavy nuclei, in particular iron.

In this article main techniques of shielding are considered, specifically for protection of astronauts in interplanetary flights or in space stations in deep space. In Section 2 it is introduced and discussed the convolution (dubbed MaxSPE) of the energy spectra of the fluence of protons of the most energetic and intense SPE in last five decades. Its energy spectrum is useful as a reference spectrum in discussing the range of the proton energies dangerous to the health of astronauts. The protection from ionizing radiation by passive methods is discussed in Section 3. The criteria are applied to the needed protection from SPEs in the 'Mars fly-by' initiative (Section 3.2). In Section 4 active methods are considered. In last decade particular attention was dedicated to shielding by magnetic fields produced by systems of superconducting coils. The approach was progressive, from a magnetic lens protecting a 'shelter' from solar flares (that are quasi-directional) and the first part of most of CMEs before they become isotropic (Section 4.1), to the full protection of a large volume 'habitat' from GCRs (Section 4.2) and the last activities on this thematic (Section 4.3).

2. The maximum Solar Particle Event

The fluence of the most intense SPEs of last 5 decades is shown in Fig. 1 as a function of the energy of the emitted

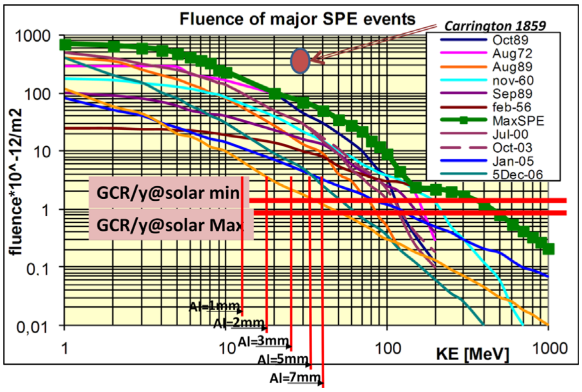

Fig. 1. Fluence vs proton energy of the most intense SPEs of last 5 decades.

particles (essentially protons). In order to appreciate the hazard that SPEs represent to humans their fluence must be compared to fluence of GCRs in a long period of time, e.g. one year, which depends on the 11-year cycle of solar activity. It exceeds in any case for more than a factor 2, the dose limits recommended by space agencies for astronauts[1] [1]. Therefore to cope with them the SPE fluence must be reduced by a suitable shield to less than 1/5 of the level of fluence of GCRs in one year at minimum solar activity, i.e. under $\approx 0.5 \times 10^{12}$ particle/m^2.

The convolution of all SPEs is marked in Fig. 1 as MaxSPE event. It can be assumed as the 'maximum SPE' from which astronauts must be shielded. The soft particles are easily absorbed in the wall of the habitat of the spacecraft (for ISS-like modules the thickness is 7 mm of aluminum, enough for stopping protons up to 40 MeV). The MaxSPE fluence is kept higher than the needed limit up to more than 400 MeV. However it must be observed that beyond 150 MeV the trend of MaxSPE is given by only one SPE, that of February 1956, whose energy spectrum was measured indirectly, and not in space, by neutron monitors on ground. From an historical point of view it is therefore justified to assume 250 MeV as the maximum dangerous energy of the particles of the MaxSPE[2]. In conclusion it is important that the shielding system to be added to the habitat of the spaceship allows covering the important range between 40 and 250 MeV of the protons, the contribution of other components in SPE being negligible. It is very important to stress that the MaxSPE fluence at 30–40 MeV is by two orders of magnitude higher than the GCR fluence in one year. Therefore SPEs are potentially lethal events, and the effective protection against them is mandatory in each either short or long duration interplanetary flight.

3. Methods for protecting: passive shielding

Bulk shielding for absorbing particles in the dangerous range of energy of SPEs poses weight problems on the spacecraft. A heavy load, added purely for reducing radiation exposure, becomes a substantial mass penalty and may dramatically increase the mission cost. It must be provided a "storm shelter", i.e. a heavily shielded (by about 20–30 g/cm^2 of water or Al) small volume; it was foreseen on the design of interplanetary vehicles [5]. Calculations and measurements show that light, highly hydrogenised materials are ideal for space radiation shielding [6]. Water is usually assumed as a reference material. In most of the solar events the energetic particles arrive at the beginning of the SPE from a determined direction in the plane of the ecliptics along an Archimedes spiral trajectory. This is true

[1] Recommended limits for astronauts depend on their gender and age [1]. Nowadays they are given as 'carrier limits' and range from 0.4 to 1.7 Sv/10 year (about 0.16–0.7 Gy/10 year) for women and from 0.7 to 3.0 (about 0.3–1.2 Gy/10 year) for men, i.e. a factor 10–5 less than the yearly exposition to GCRs at minimum solar activity.

[2] The MaxSPE in Fig. 1 has been constructed taking into account only a negligible part (the part with direct measurements in space) of the long solar history. As a 'warning' of this serious limitation it is reported in Fig. 1 the fluence for KE > 30 MeV of the Carrington event of 1859 [2,3] is likely the largest 'proton enhancement' in the 1561–1994 period [4].