Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 59 (2017) 1473–1485

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

The radiation shielding potential of CI and CM chondrites

Leos Pohl *, Daniel T. Britt

Department of Physics, Physical Sciences Bldg. 430, University of Central Florida, 4111 Libra Drive, Orlando, FL 32816-2385, USA

Received 30 August 2016; received in revised form 4 December 2016; accepted 17 December 2016
Available online 28 December 2016

Abstract

Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs) pose a serious limit on the duration of deep space human missions. A shield composed of a bulk mass of material in which the incident particles deposit their energy is the simplest way to attenuate the radiation. The cost of bringing the sufficient mass from the Earth's surface is prohibitive. The shielding properties of asteroidal material, which is readily available in space, are investigated. Solution of Bethe's equation is implemented for incident protons and the application in composite materials and the significance of various correction terms are discussed; the density correction is implemented. The solution is benchmarked and shows good agreement with the results in literature which implement more correction terms within the energy ranges considered. The shielding properties of CI and CM asteroidal taxonomy groups and major asteroidal minerals are presented in terms of stopping force. The results show that CI and CM chondrites have better stopping properties than Aluminium. Beneficiation is discussed and is shown to have a significant effect on the stopping power.

Keywords: Radiation shielding; ISRU; Asteroid regolith; Stopping power; Human exploration

1. Introduction

Space radiation is a significant obstacle in deep space human exploration. This radiation can be understood as a flux of energetic particles which deposit energy in matter and subsequently represent a serious risk for both living organisms as well as sensitive apparatuses. All energetic particles (atoms, atomic nuclei, protons, neutrons, electrons, positrons, pions, photons, etc.) can interact when traversing through matter. One of the quantifying parameters of their detrimental effect is how much energy is released per unit traversed length — *Linear Energy Transfer* (LET).

As we briefly discuss in Section 1.1, the source radiation in space consists mostly of atomic nuclei, charged particles, which are predominantly protons. The foremost concern is thus slowing down these charged particles. Although all four fundamental forces play role during the interaction of these charged particles, as they traverse in matter, their kinetic energy is predominantly lost due to electric fields. For general overview of particles and their interactions, we refer the reader to e.g. Griffiths (1987) or to a more recent publication focused on interactions in matter — Tavernier (2010).

If we neglect all the intermediate steps, the incident particle causes in the target material either an atomic or molecular excitation, ionization or change in constituents. In living organisms, specifically in cells, ionization of target material can result in production of *radicals*. These ions are highly reactive chemically and interact with the nearby atoms and molecules and break the existing chemical bonds. Oxides formed from the event help to spread the radiation damage to the neighbouring initially unaffected cells (Azzam et al., 2012). The most dangerous effect is on Deoxyribonucleic acid (DNA) within the cells. When both of the strands of DNA are broken, the cell attempts

* Corresponding author.
E-mail addresses: pohl@knights.ucf.edu (L. Pohl), britt@physics.ucf.edu (D.T. Britt).

http://dx.doi.org/10.1016/j.asr.2016.12.028
0273-1177/

to repair them which may result in an incorrect "reconnection" of the strands and either a mutation or a chromosome abnormality occurs or the cell dies (if only a single strand of DNA is broken, the other can serve as a template for the repair and the risk of erroneous recombination is smaller).

Because of these effects, a shield of a sufficient mass and a proper composition encompassing a spacecraft is necessary to provide protection during deep space missions. However, the costs of transportation of the required mass of such a shield from the Earth surface are very high. Another option is to use material that is in a less deep potential well (the Moon) or material already in space (asteroids). The feasibility of using the lunar regolith as a shielding material against high energy particles was analysed by several authors, for instance Miller et al. (2009) who measured dose reduction properties of lunar soil or Pham and El-Genk (2009) who used the Monte Carlo radiation transport code to calculate the effects of lunar soil on the attenuation of Solar Energetic Particle events. In this work, we focus on the shielding properties of asteroidal material.

1.1. Sources of energetic particles in space

Energetic particles permeating the interplanetary space are supplied by Solar Energetic Particle (SEP) events and Galactic Cosmic Rays (GCR). The particles from these two sources primarily differ in spectrum as well as in their temporal and spatial variability.

1.1.1. Solar Energetic Particles

Solar Energetic Particles (SEPs) are ions and electrons which originate in the solar flare regions. The flux of SEPs strongly depends on variability of solar magnetic field. Because the flux of particles can increase by several orders of magnitude due to solar activity, we can consider these as temporal events. An important question for any shield construction is whether we can predict these events which has direct consequences for the design of a useful shield in a spacecraft.

Two main warning signs of an SEP emission can be observed. The first one is the gradual increase in particle flux. Although in many cases the intensity of particle flux rises gradually (usually it takes a few hours before the maximum intensity is attained (Mewaldt et al., 2005)), the events on 20th January 2005 and in February 1956 showed that a rapid increase in flux can happen relatively unexpectedly (e.g. for the 2005 event, the peak flux of protons with energies > 100 MeV was reached within ~ 30 min) (Mewaldt et al., 2005; Meyer et al., 1956) and there is very little time for taking precautions. Both events were characterized by a very steep increase in the proton flux and relatively high intensities of the incident particles. An increase in X-Ray and radio emissions can be another warning sign. While it takes only about 8 min 20 s for electromagnetic radiation to reach the Earth's orbit, 10 MeV protons need about 80 min, however, 100 MeV protons only about 27 min and 500 MeV protons only ~ 14 min.

Table 1
Most abundant elements in per cents in SEP normalized to Hydrogen, data is based on Reames (1995).

Element	Abundance
H	100.0
He	3.631
C	0.030
O	0.064
Mg	0.012
Ne	0.010
N	0.008

In large SEP events the energies of the solar protons can reach up to several GeV. We present the elemental abundance of SEPs in Table 1 which illustrates the predominance of protons.

1.1.2. Galactic Cosmic Rays

Galactic Cosmic Rays (GCRs) are energetic particles that originate outside our Solar system. They consist mostly of ionized nuclei. The observable energy spectrum is limited from below to 200–300 MeV (due to solar wind induced magnetic field and interactions with interstellar matter). GCRs are affected by the Solar cycle and therefore the flux of GCRs is time and place dependent in the similar way as for SEPs, however, the relation is inverse — the larger solar activity (and thus stronger particle flux from the Sun), the larger the inhibiting magnetic field and the more attenuated the GCRs. From about 10 GeV for protons the magnetic field has little effect on the particles (Biermann and Sigl, 2001). We present the observed GCR spectra of the first 8 elements in Fig. 1 which suggests the predominance of protons (with a more significant ratio of α particles than in SEPs).

1.2. Asteroidal mineralogy

Composition of asteroids is different from that of lunar regolith to a degree that it is not a priori possible to conclude that asteroid material has the same shielding properties as lunar regolith and it is not possible to reuse the already available results. The major difference is in phyllosilicate content. These layered hydrated sheets of silicates are abundantly found in carbonaceous chondrites, specifically in CM, CR and CI groups while missing in the lunar regolith (Heiken et al., 1991).

The significance of phyllosilicates for shielding against high energy particles lies in their water and hydroxyl content[1] which can be up to 12.5% of their weight (Alexander et al., 2013). Water has very good properties not only for slowing down (shielding) charged energetic particles (GCR and SEP) but it also has a large cross section for interaction with neutrons which result from

[1] Throughout the work we use the words water and hydrated to suggest the presence of either water or hydroxyl molecules.