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Estimation of Galactic Cosmic Ray exposure inside and outside the Earth's magnetosphere during the recent solar minimum between solar cycles 23 and 24

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Abstract

The evidently low solar activity observed between solar cycles 23 and 24 during the years 2008–2010 led to a substantial increase in the Galactic Cosmic Ray (GCR) intensity in comparison with preceding solar minima. As the GCRs consist of highly-ionizing charged particles having the potential to cause biological damage, they are a subject of concern for manned missions to space. With the enhanced particle fluxes observed between 2008 and 2010, it is reasonable to assume that the radiation exposure from GCR must have also increased to unusually high levels. In this paper, the GCR exposure outside and inside the Earth's magnetosphere is numerically calculated for time periods starting from 1970 to the end of 2011 in order to investigate the increase in dose levels during the years 2008–2010 in comparison with the last three solar minima. The dose rates were calculated in a water sphere, used as a surrogate for the human body, either unshielded or surrounded by aluminium shielding of 0.3, 10 or 40 g/cm^2.

By performing such a long-term analysis, it was estimated that the GCR exposure during the recent solar minimum was indeed the largest in comparison with previous minima and that the increase was more pronounced for locations outside the magnetosphere.

Keywords: Radiation exposure in Low Earth Orbit and near-Earth interplanetary space; Variation of dose rates with shielding over time; Galactic Cosmic Rays; Solar minimum; Monte-Carlo simulations

1. Introduction

The expansion of human space exploration to destinations like the Moon and Mars is likely to occur within the first half of this century. Additionally, the opportunities for the general public travelling into space with commercial spaceflights are becoming reality. With the rising number of people visiting and likely to visit space, the studies improving the knowledge on health risks related to the exotic environment encountered in space are of great importance as they can help to reduce these risks.

One of the primary concerns for manned missions to space is the elevated level of radiation exposure especially due to Solar Particle Events (SPE) and Galactic Cosmic Rays (GCRs) (NCRP, 1989, 2000, 2002, 2006; Cucinotta et al., 2001; Cucinotta and Durante, 2006). High-energy GCR nuclei, ranging from hydrogen to iron and beyond, contribute to the significant amount of dose to which astronauts are exposed to both outside and inside the Earth's magnetosphere (NCRP, 2000, 2006). The dose levels are directly related to the GCR particle intensities which vary with the 11-year sunspot cycle and the 22-year solar magnetic cycle (Belov, 2000; Heber, 2011; Usoskin et al.,

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2001). Since the GCR intensity is anti-correlated with the solar activity, the GCR exposure peaks at solar minimum and is lowest at solar maximum conditions.

During the last solar minimum between the solar cycles 23 and 24 an unusual rise in the GCR intensity in comparison with several minima in the past decades was observed. This phenomenon was related to the unusually low solar activity during the extended solar minimum conditions in the heliosphere (Mewaldt et al., 2010). In this work, the increase in the GCR exposure during the last solar minimum is investigated for the orbit of the International Space Station (ISS) and for near-Earth interplanetary space at a distance of one Astronomical Unit (AU) from the Sun outside the Earth's magnetosphere. The exposure was estimated in terms of absorbed dose and dose equivalent rates for a period ranging from January 1970 to October 2011 in order to examine the relative change in the dose quantities at different solar minima. The GCR model recently developed by Matthiä et al. (2013a) was employed in the work since other models used for dosimetric purposes like CREME96 (Tylka et al., 1997; https://creme.isde.vanderbilt.edu/), CREME2009 (https://creme.isde.vanderbilt.edu/) and the Badhwar-O'Neill 2010 model (O'Neill, 2010), were found not to be able to describe the increased GCR intensity and the respective increase in dose during 2008–2010 as presented in Mrigakshi et al. (2012) and Mrigakshi et al. (2013).

A similar study numerically determining the GCR exposure over the time period between the years 1975 and the end of 2009 was performed by Schwadron et al. (2010) who did not predict a significant increase in dose rates between the years 2008 and 2010. One of the reasons for this is likely due to the application of the Badhwar-O'Neill 2006 GCR model (O'Neill, 2006) by Schwadron et al. (2010) to estimate the radiation exposure. The authors mention in the paper that the value of the solar modulation parameter Φ, frequently used for the description of the modulation of GCR in the heliosphere in the force field model (Gleeson and Axford, 1968), ranged between 400 MV and 1800 MV in the model from solar minimum to maximum during the inspected time period. This parameter gives an indication about the strength of the solar modulation in the Heliosphere. A smaller Φ implies weaker modulation allowing more GCR particles to penetrate inside the heliosphere. In Section 1.1 the value of Φ based on GCR measurements during the solar minimum in late 2009 is shown to have been much lower than the value used by the GCR model from O'Neill (2006) to describe the GCR spectra during that time period.

1.1. GCR during the solar minimum between solar cycles 23 and 24

Since the discovery of GCR by Victor Franz Hess (Hess, 1912) a century ago, a large number of GCR measurements by various ground-based, high-altitude balloon-borne and space-borne instruments have been performed (Grieder, 2001 and the references therein). Continuous data especially from Neutron Monitors (NM) (Simpson, 2000) since 1951 complemented by recent space missions like the Advanced Composition Explorer (ACE) (Stone et al, 1998) which has been operating since 1997 are of special importance as they reveal the long-term variation of the GCR intensity. Among others, ACE measures nuclei from Li to Ni over an energy range from about 40 to 500 MeV/nuc while the Neutron Monitor count rates provide an indirect measure of the GCR intensity (Usoskin et al. 2001).

Fig. 1a shows the temporal variation of the monthly sunspot numbers (http://sidc.oma.be/DATA/monthssn.dat) with the solar cycle number indicated and Fig. 1b shows the NM count rates measured by the Oulu station (http://cosmicrays.oulu.fi/) from January 1970 to October 2011. The Oulu station is located at 65.05°N, 25.47°E where the geomagnetic shielding quantified by the effective vertical cut-off rigidity is about 0.8 GV. The rigidity R of a charged particle is defined as its momentum p per charge q, $R = p/q$. The effective vertical cut-off rigidity lies in the rigidity interval between the value below which no particle arrives in vertical direction at the location of interest and the highest rigidity value above which

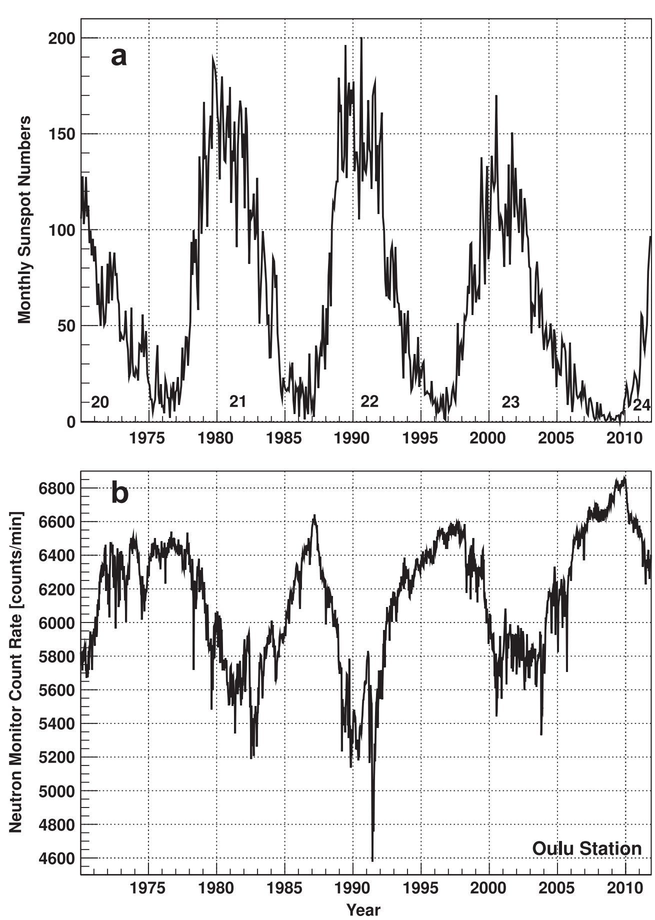

Fig. 1. Monthly sunspot numbers and solar cycle numbers from 20 to 24 (Fig. 1a). 10-day averaged neutron monitor count rates from the Oulu station starting from 1970 to the end of 2011 (Fig. 1b).