Global Cosmic Ray Cutoff Rigidities Over the Past 2000 Years

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Abstract

We investigate the evaluation of global cosmic ray cutoff rigidities for the past 2000 years. The paper puts its focus on changes in the strength of the geomagnetic dipole and in its position inside the Earth. Possible effects are discussed for a cutoff rigidity fiducial mark that is especially suited for the evaluation of production rates of cosmogenic nuclides in the Earth's atmosphere.

1. Introduction

One of the factors responsible for the long-term changes in the production rates of cosmogenic nuclides in the Earth's atmosphere is secular variations in the geomagnetic field. The shielding effect of the Earth's magnetic field and its variation must therefore be taken into account for a proper identification of solar and heliospheric variability in the indirect information provided by cosmogenic nuclides stored in terrestrial archives.

Geomagnetic effects on cosmic rays are usually described by the concept of cutoff rigidities [8]. The state-of-the-art technique for the determination of cutoff rigidities is the calculation of particle trajectories in a magnetic field model representing the Earth's magnetic field at a specific time. For a specified location (geogr. latitude Λ_0 and longitude φ_0), and a specified arrival direction (zenith angle ϑ, azimuth angle ϕ), allowed and forbidden trajectories are determined by numerically integrating the equation of motion of charged particles as a function of particle rigidity. The effective cutoff rigidity $R_{c,eff}(\Lambda_0, \varphi_0, \vartheta, \phi)$ takes into account geomagnetic filtering effects in the penumbra region [2].

Today the Earth's magnetic field is described by magnetic field models which include internal and external sources, as e.g. the International Geomagnetic Reference Field (IGRF) [5]. Unfortunately, such magnetic field models are not available for the past. Simple dipole field models are therefore often used for palaeogeophysical studies. The global magnetic dipole moment and the location of the North geomagnetic pole are thereby determined from archaeometric information.

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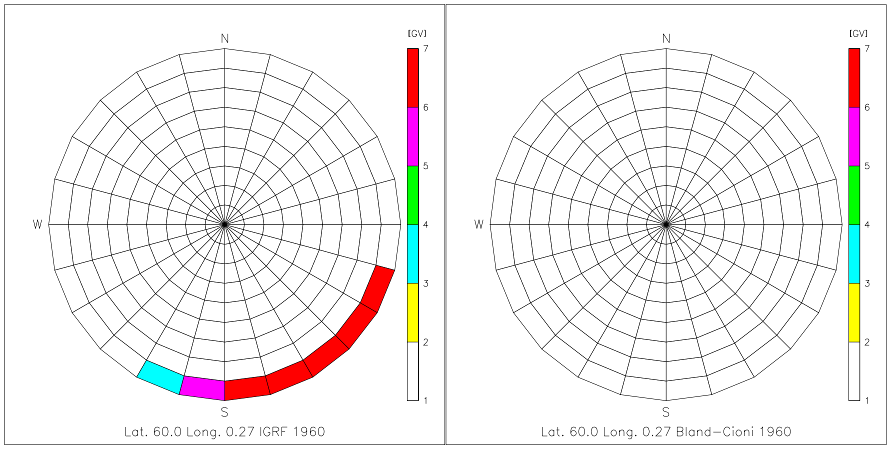

Fig. 1. Effective geomagnetic cutoff rigidities in dependence of the arrival direction for 60°N, 0.27°E. Left: Results obtained by using the trajectory-tracing technique and the IGRF for Epoch 1960.0. Right: Corresponding results obtained according to the method of Bland and Cioni [1].

2. Local Cutoff Rigidities

Fig. 1 illustrates the cutoff rigidities and their dependence on the direction of incidence at a specific location. The left panel shows the effective geomagnetic cosmic ray cutoff rigidity calculated for 193 arrival directions at 60°N, 0.27°E by using the trajectory-tracing technique with a GEANT4 program [4,3] and the IGRF, Epoch 1960.0. These cutoff rigidities are compared to results obtained by the method of Bland and Cioni [1]. Their method of deducing off-vertical cutoff rigidities analytically from effective vertical cutoff values is often used (e.g. by Masarik and Beer [6]) for the evaluation of production rates of cosmogenic nuclides. It is evident that significant differences exist at high zenith angles.

At a specific location, the cutoff rigidity

$$\overline{R}_{c,eff}^{\vartheta_{max}} = \frac{\int_0^{2\pi} \int_0^{\vartheta_{max}} R_{c,eff}(\vartheta, \phi) \sin\vartheta \, \mathrm{d}\vartheta \, \mathrm{d}\phi}{2\pi \int_0^{\vartheta_{max}} \sin\vartheta \, \mathrm{d}\vartheta} \tag{1}$$

is a valuable parameter describing the lower rigidity limit of cosmic ray particles arriving at this location. The values of $\overline{R}_{c,eff}^{\vartheta_{max}}$ corresponding to the results presented in Fig. 1 are listed in Table 1 for $\vartheta_{max} = 45°$ and $\vartheta_{max} = 85°$.

3. Global Cutoff Rigidities

During the past 2000 years the magnetic dipole moment decreased by ~30 % to todays value of ~7.8·10^{15} Vsm, and the location of the North geomagnetic pole has changed within a limited latitudinal range near the geographic

Table 1. $\overline{R}_{c,eff}^{\vartheta_{max}}$ as obtained from the results shown in Fig. 1.

Location	ϑ_{max}	Trajectory-tracing	Bland and Cioni
60°N, 0.27°E	45°	1.24 GV	1.19 GV
	85°	1.55 GV	1.19 GV

pole [7]. In this study we focus on the effects of changes in the strength of the geomagnetic dipole and in its position inside the Earth on the evaluation of cutoff rigidities for the past. Examples of contour lines of 2π-averaged cutoff rigidities $\overline{R}_{c,eff}^{85°}$ are plotted in Fig. 2. For the corresponding calculations the information about the position and direction of the magnetic dipole inside the Earth was deduced from the IGRF, Epoch 1995.0, coefficients. Fig. 3 shows the contour line for $\overline{R}_{c,eff}^{85°} = 2$ GV in the Northern and Southern hemispheres for geocentric and eccentric dipole field models (geomagnetic dipole moment $7.8 \cdot 10^{15}$ Vsm). The total area enclosed by the solid contours (geocentric dipole) in the North and South corresponds to ~15 % of the Earth's surface. With the eccentric geodipole instead of the geocentric dipole the surface inside the 2 GV contour line is reduced in the North by ~ 7 % and enlarged in the South by ~ 6 %.

4. Summary

For the evaluation of production rates of cosmogenic nuclides at selected locations, uncertainties in the cutoff rigidities may have significant consequences. In particular, as illustrated in Fig. 3, the use of a geocentric instead of the eccentric dipole field may lead to considerable differences between the Northern and Southern hemispheres.

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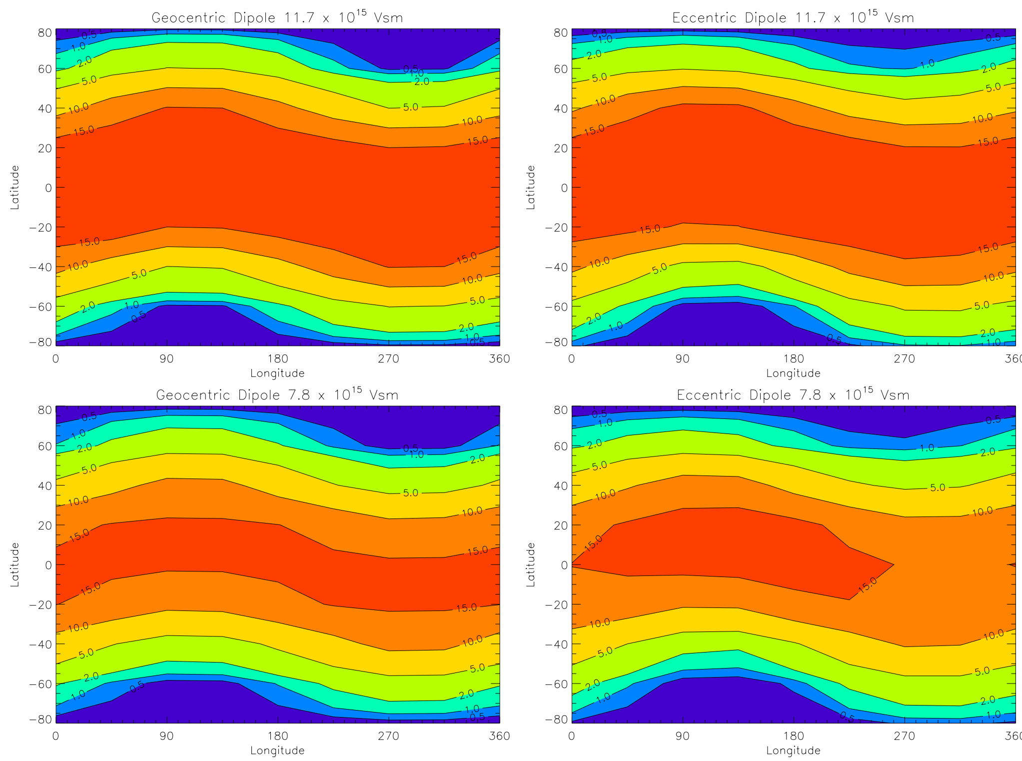

Fig. 2. Global contours of trajectory-derived averaged magnetic cutoff rigidities $\overline{R}_{c,eff}^{85^\circ}$ for a dipole field model with dipole moment $11.7 \cdot 10^{15}$ Vsm (top panels) and $7.8 \cdot 10^{15}$ Vsm (bottom panels), calculated for a geocentric (left) and for an eccentric magnetic dipole (right). For details see text.

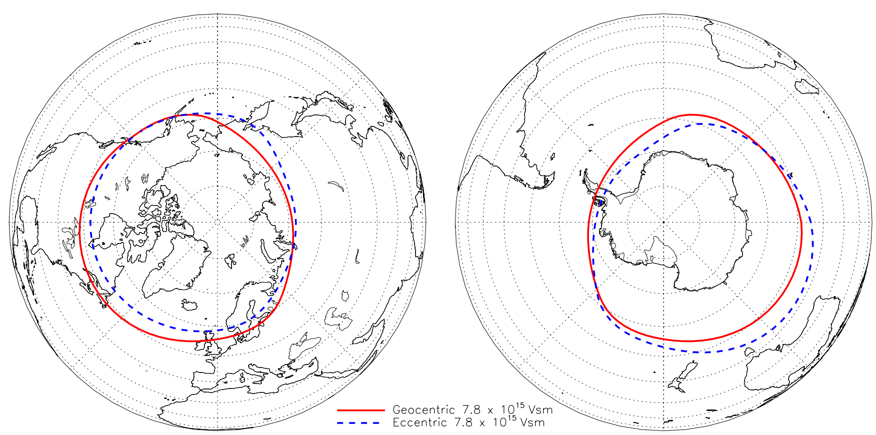

Fig. 3. Contour lines for $\overline{R}_{c,eff}^{85^\circ}$ =2 GV in the Northern (left) and Southern (right) hemispheres for geomagnetic dipole moment $7.8{\cdot}10^{15}$ Vsm. The solid lines refer to a geocentric magnetic dipole, whereas the dashed lines refer to an eccentric dipole. For details see text.