Long-Term Cosmic Ray Intensities: Physical Reconstruction

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Abstract

Solanki et al. (2000) have recently calculated the open solar magnetic flux for the last 400 years from sunspot data. Using this reconstructed magnetic flux as an input to a simple spherically symmetric quasi-steady state model of the heliosphere, we calculate the expected differential spectra and integral intensity of galactic cosmic rays at the Earth's orbit since 1610. The calculated cosmic ray integral intensity is in good agreement with the neutron monitor measurements during the last 50 years. Moreover, using the specific yield function of cosmogenic ^{10}Be radionuclide production in the atmosphere, we also calculate the expected ^{10}Be production rate which exhibits an excellent agreement with the actual ^{10}Be abundance in polar ice over the last 400 years.

Here we present a physical model for the long-term reconstruction of cosmic ray intensity at 1 AU. The reconstruction is based on a combination of the solar magnetic flux model and a heliospheric model. This model allows us to calculate the expected intensity of galactic cosmic rays (GCR) at the Earth's orbit for the last 400 years. Details can be found in [25].

Using the numerical recipe of Solanki et al. [21] and the group sunspot number series (Fig. 1.a) [11] we have calculated the open solar magnetic flux F_o since 1610 as shown in Fig. 1.b. In order to calculate galactic cosmic ray (GCR) spectra we use a spherically symmetric quasi-steady stochastic simulation model described in detail elsewhere [24], which reliably describes the long-term GCR modulation during the last 50 years. In this model, the most important parameter of the heliospheric modulation of GCR is the modulation strength [10]: $\Phi = (D - r_E)V/(3\kappa_o)$, where $D = 100$ AU is the heliospheric boundary and $r_E = 1$ AU, $V = 400$ km/s is the constant solar wind velocity and κ_o is the rigidity independent part of the diffusion coefficient. Thus, all changes in the modulation strength Φ in our model are related to the changing diffusion

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coefficient κ_o. We calculate the GCR spectrum at 1 AU for different values of the modulation strength Φ, using the local interstellar spectrum of GCR as given by [6]. Then the response of a neutron monitor (NM) to cosmic rays (the count rate) was calculated using the NM specific yield function [9],[17]. The diffusion coefficient κ_o depends inversely on the interplanetary magnetic field strength B because of a stronger scattering of cosmic ray particles in an enhanced magnetic field [19],[26]. On the other hand, the open solar magnetic flux is by definition proportional to B. Therefore, we expect the following rough relation between the modulation strength and solar magnetic flux $\Phi(t) \propto {F_o}^n$. This relation was studied in [25] and it was shown that $n \approx 1$ but is slightly different for ascending and descending phases of the solar cycle. This drift-related hysteresis effect results from the different modulation for the same solar conditions during different phases of the solar cycle (see, e.g., [4]). However, this hysteresis effect is only important on time scales shorter than the 11-year cycle.

We calculated the modulation strength Φ for the last four centuries (Fig. 1.c) from the open solar magnetic flux F_o (Fig. 1.b). Note that, since the model [21] is based upon sunspot activity, the magnetic flux approaches zero during the deep Maunder minimum. However, solar, heliospheric and magnetospheric variation is known to exist during that period, although at a very low level [7],[23]. Therefore, an exact reconstruction of Φ during the Maunder minimum is not possible on the basis of this method. From the calculated Φ we have computed the count rate of the standard NM for the entire 400-year interval (Fig. 1.d). This reconstructed NM series shows a trend in the cycle maximum level of about -0.5 % per cycle during the last 100 years in agreement with the results obtained for the last 5 cycles [1],[22]. However, this trend is not persistent throughout the entire 400-year interval, contrary to the suggestion by [22] who interpreted the trend in terms of a possible supernova explosion in the vicinity of the solar system. Note that our reconstructed GCR intensity (Fig. 1.d) differs from that by Lockwood [13] for the last 140 years. As discussed in [16] Lockwood's GCR intensity shows a very steep decreasing trend of about -2 % per solar cycle, exceeding the unmodulated LIS level (given by the maximum of flux range included in Fig. 1.d) around 1900. However, it has been estimated from various indirect proxies that the GCR intensity was well below LIS at that time [5],[15],[18],[20]. Our model agrees with these estimates, predicting that the GCR intensity was indeed significantly below LIS around 1900.

From the calculated GCR spectra and using the cosmogenic ^{10}Be production rate model [14], we calculated the 11-year smoothed ^{10}Be level during the last 400 years. The calculated ^{10}Be levels are plotted in Fig. 1.e together with the actual data from Greenland [3] and Antarctica [2]. The cross-corellation between the calculated and actual data is 0.86 and 0.84 for the Greenland and Antarctic series, respectively. There are two periods when the reconstructed and the mea-

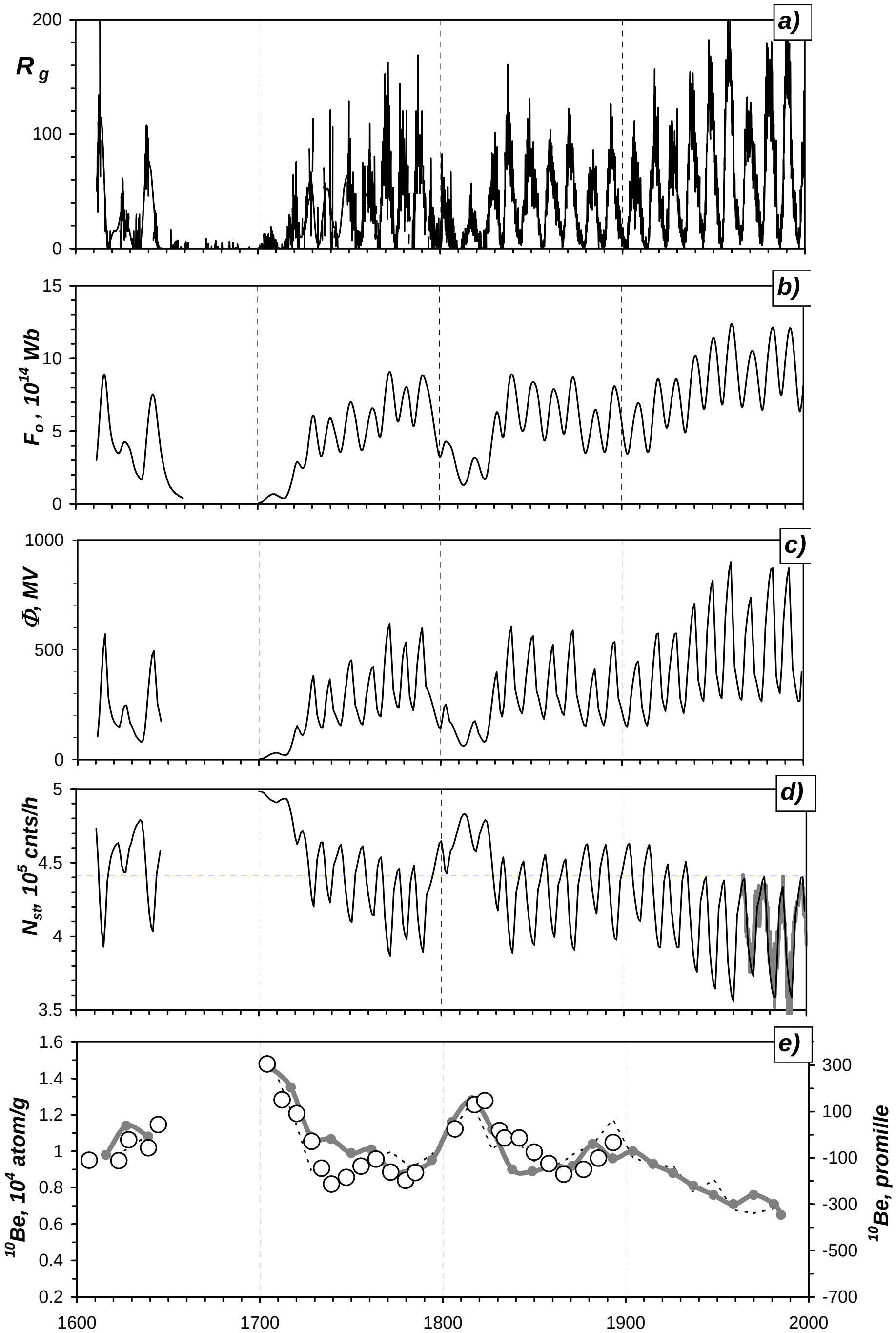

Fig. 1. (a) Monthly group sunspot numbers [11]. (b) The reconstructed open solar magnetic flux F_o. (c) The calculated modulation strength Φ. (d) The reconstructed count rate of the standard neutron monitor (1-NM64 at sea level) for the geomagnetic cutoff 0.8 GV. The actual scaled Oulu NM count rate is shown in grey for 1964–2000. The horizontal dotted line denotes the highest actually recorded NM count rate in May 1965. (e) 11-year smoothed series of ^{10}Be abundance in polar ice in Greenland (dashed line, left axis) [3] and the model GCR flux (solid line). Big dots and right axis correspond to the Antarctic [2] ^{10}Be series.

sured long-term ^{10}Be series deviate from each other: in 1730–1750 and 1830–1850. These periods occurred fairly soon after the Maunder and Dalton minima, respectively, and were characterized by a reduced temperature at the Earth's surface: the Little Ice Age and the cold spell in the first half of 19^{th} century, respectively (see, e.g., [8]). Local climatic effects are known to play a role in the deposition of ^{10}Be in polar ice [3],[12]. Therefore, the differences between the modeled and the measured records may be related to significant variations of climatic conditions and resulting changes in the ^{10}Be deposition during these periods.

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