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Use of cosmogenic radionuclides ^{14}C and ^{10}Be to verify cosmic ray modulation reconstructed since 1616

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Here we present a new semi-empirical model describing modulation of galactic cosmic rays in the heliosphere. The model is an update of the previous similar model by Alanko-Huotari et al. (2006) and considers such heliospheric parameters as open solar magnetic flux, heliospheric current sheet tilt angle and the large scale solar magnetic field polarity. The model has been tested and calibrated for the period 1976 - 2013 including the very weak solar activity minimum in 2008-2010. Based on this model, and on different reconstructions of the open solar flux, the heliospheric modulation potential is reconstructed since 1610, and subsequently used to compute the production and distribution of cosmogenic radionuclides, such as ^{10}Be and ^{14}C in the terrestrial system. The modelled values are compared with those measured in archives from ice cores and tree rings confirming the validity of our model.

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1. Introduction

When Galactic Cosmic Rays (GCRs) enter the heliosphere, they undergo a series of interactions with the expanding solar wind, the embedded Heliospheric Magnetic Field (HMF) and the Heliopsheric Current Sheet (HCS). This interplay leads to spatial and temporal variations of the GCRs flux, known as heliospheric modulation of GCRs. In 1960s a theory was developed that fully describes the propagation of GCRs within the heliosphere and can be summarised in the Parker's transport equation (Parker 1965; Krymskij 1969). Solving this equation has been of high interest when it comes to studying the solar variability and its effects on cosmic rays. Although fully developed and complex theoretical 3-D approaches to Parker's transport equation exist (Potgieter 2013, and references therein), the involved parameters cannot be directly measured, making it difficult to investigate their goodness using realistic input parameters. Therefore, empirical models that associate the cosmic rays variations with different observable heliospheric parameters are also useful. Even though some progress has been made in this direction, there are still limitations in some of these empirical models. For instance, Sabbah and Rybanský (2006) and Stozhkov et al. (2004) consider time series from a single neutron monitor or at a fixed energy respectively. Long-term effects are often omitted (e.g. Belov et al. 2006).

Here we take into consideration a simplified approach to Parker's equation, the so called force field approximation (Gleeson and Axford 1968; Caballero-Lopez and Moraal 2004). In this case the modulation potential, ϕ, which parametrises the GCRs modulation at 1AU and represents the particles' energy losses within the heliosphere, is inversely proportional to the diffusion coefficient. The later is inversely proportional to the intensity of the HMF, therefore, one can expect that the modulation potential is roughly proportional to the magnetic field density. Following this and the empirical approach by Alanko-Huotari et al. (2006), we attempt to relate ϕ with heliospheric parameters, using observational data for the period 1951-2013. In our semi-empirical approach we are interested only in the heliospheric parameters that do not show spatial variations, therefore they describe the global heliosphere, and in addition are recorded continuously over a long period of time. Such parameters are the HCS tilt angle, α, the HMF polarity, p, and the open solar magnetic flux (OSMF), F, with the latter replacing the strength, B, as a global parameter of the HMF. To further test the validity of our model, we used the reconstructed modulation potential to estimate the global production of radiocarbon ^{14}C and beryllium ^{10}Be. The results were compared with records from terrestrial archives such as tree rings and ice cores, showing a good agreement.

The HCS tilt angle, α is an important factor of cosmic rays modulation. The Wilcox Solar Observatory (WSO) carries out observations of the HCS and provides α, reconstructed for each Carrington Rotation (CR), since May 1976. For the purpose of fitting parameters in the modulation potential model since 1951 and also to reconstruct ϕ in the past until approximately the 1600, we need to reconstruct the tilt angle over that period of time. In this view we have also developed a model describing the tilt angle 11-year cyclic variations. Within one solar cycle the latitudinal extend of the HCS can vary from $5-10^\circ$, during the years of minimum solar activity, and up to 70° or more, when the solar activity reaches its maximum. Moreover, α does not depend on the amplitude of the solar cycle but it exhibits a cyclic behaviour (Hoeksema 1991; Suess et al. 1993) that only depends on the phase of the solar cycle. Accordingly, one can reconstruct and even predict α by only knowing the solar cycle dates. The idea of a cyclic behaviour of the tilt angle was adopted by Alanko-Huotari et al. (2007), who developed an empirical model to reconstruct the tilt angle values in the past. Here this model is revisited, using the WSO database which currently extends until 2014.

To fit the parameters in the HCS tilt angle cyclic model, we used the values of the maximum latitudinal extent of the HCS, based on the radial model, as provided by the WSO for Carrington rotations (http://wso.stanford.edu/Tilts.html). Annual values are derived by averaging the values produced by WSO over a calendar year. In the modulation model, the fitted parameters are derived using the annual averages of the modulation potential, calculated from ground based cosmic rays observations (Usoskin et al. 2005, 2011) for the period 1951-2014. We also used the reconstructed data of the OSMF by Lockwood and Owens (2014); Lockwood et al. (2014) for fitting the parameters and Jiang et al. (2011) for comparison purposes. The HMF polarity is defined as $p = 1$ for positive polarity periods, $p = -1$ for negative polarity periods and $p = 0$ for the years when polarity reverses. Based on the WSO polar field observations since 1976, the polarity reversed on years 1980, 1990, 2000, 2013. For the period before 1976, the maxima of the solar cycles are considered as the years the polarity reverses. The tilt angle values used, for the parameter fitting in the modulation model, are the ones calculated using our empirical model. To test the validity of the modulation model we also use the radionuclides ^{14}C and ^{10}Be records, stored in terrestrial archives such as tree rings (Roth and Joos 2013) and ice cores (Berggren et al. 2009).

2. Tilt angle model

The best-fit empirical model for the annual reconstruction of the HCS tilt angle is found to take the form:

$$\alpha_i = \begin{cases} \min\left(70; 1.5^\circ + 909.5^\circ \cdot X_i^2\right) & \text{for } X_i \leqslant 0.4, \\ \min\left(70; 11.1^\circ + 118.8^\circ \cdot (1 - X_i)^2\right) & \text{for } X_i > 0.4, \end{cases} \tag{2.1}$$

where $X_i = i/N$, i is the year in the cycle and N is the cycle length in years: $i = [1, N]$. To define the length of the solar cycle 24, the minimum of the cycle was considered to be year 2021 (Uzal et al. 2012). Considering the asymmetry of the cyclic shape of the tilt angle (Hathaway 2010), we assume the ascending and maximum phase to be shorter than the descending phase. Because of the observational limitations, the maximum angle is set to 70° (Suess et al. 1993). The cyclic behaviour of the model and the above described features are consistent with the cyclic shape that the WSO estimated values follow (Figure 1). The two parameters follow each other closely with correlation coefficient $R = 0.956^{+0.012}_{-0.017}$. The best correlation appears during the ascending phase, corresponding to the fast monotonous rise of the tilt angle. The reconstructed tilt angle was also compared with the distribution of tilt angle estimates by Pishkalo (2006) based on image analysis of solar eclipses from 1870 through 2002. Though the later provides only rough and sparse estimates, they appear to be in good agreement (see Figure 1).

3. Modulation potential model

The modulation model we developed is of the form:

$$\phi = \phi_0 \times F^{n - \frac{\alpha}{\alpha_0}} (1 + \beta p) \tag{3.1}$$

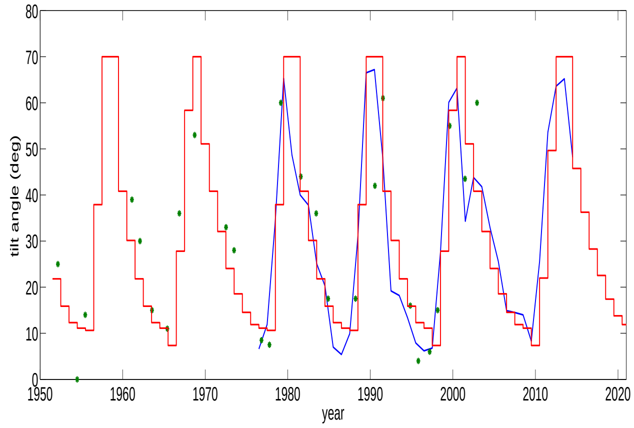

Figure 1: Annual variations of the HCS tilt angle as provided by WSO (blue solid line), and calculated from the solar cycle dates by the empirical relation described via Equation (2.1) (red curve) for the period 1951–2021. Green stars represent reconstructed HCS tilt angles for 1870 until 2002 by image analysis of total solar eclipses (courtesy of M. I. Pishkalo).

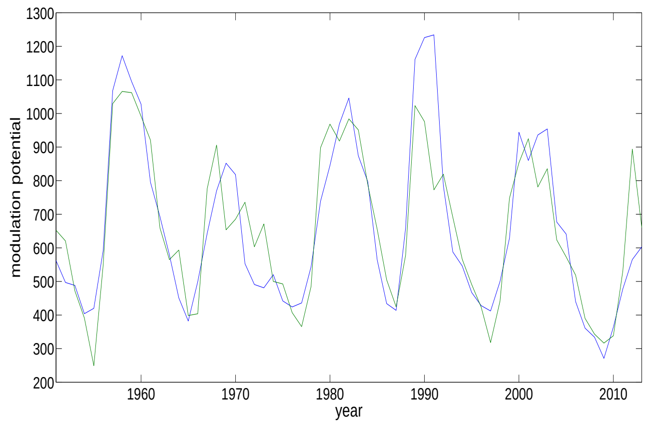

Figure 2: Annual variations of the reconstructed by ground based cosmic rays observations (blue curve) and the modelled (green curve) modulation potential for the period 1951-2013.

where $\phi_0 = 1479.4$ MV, $\alpha_0 = 145.5^\circ$, $n = 1.04$ and $\beta = -0.091$ are the best fitted parameters, using the Lockwood et al. (2014) OSMF, which is expressed in 10^{15} Wb. These parameters are chosen considering that they give good correlation between the modelled and the reconstructed from neutron monitors modulation potential with Pearson's correlation coefficient $R = 0.88 \pm 0.03$ (68% confidence level). Figure 2 shows the annual variation of the two quantities. The modelled curve follows well the one based on neutron monitor observations. There appears to be a discrepancy during the maximum of the solar cycle 22. This could be related to the high solar wind plasma flow pressure occurring between years 1991 and 1992.

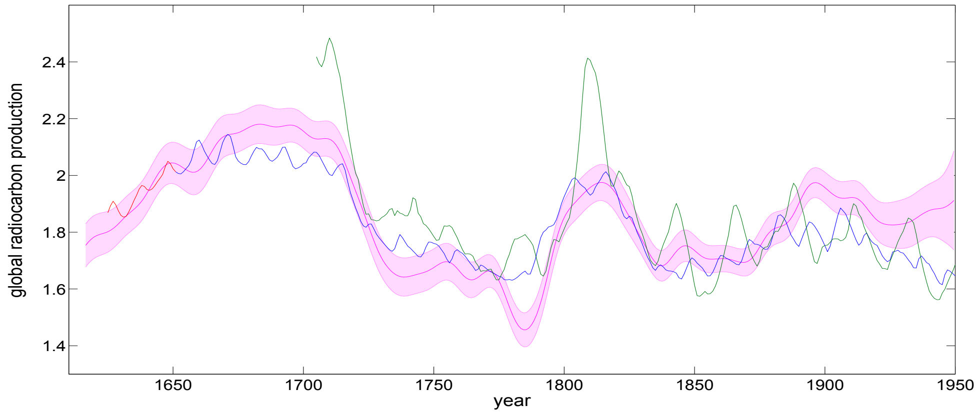

Figure 3: Annual variations of radiocarbon production and distribution modelled using the open solar magnetic flux estimated based on the Lockwood and Owens (2014); Lockwood et al. (2014) (blue curve), on the Jiang et al. (2011) (green curve). The two show a good agreement with the radiocarbon records from terrestrial archives (Roth and Joos 2013) (magenta curve with contour for the 2σ confidence level).

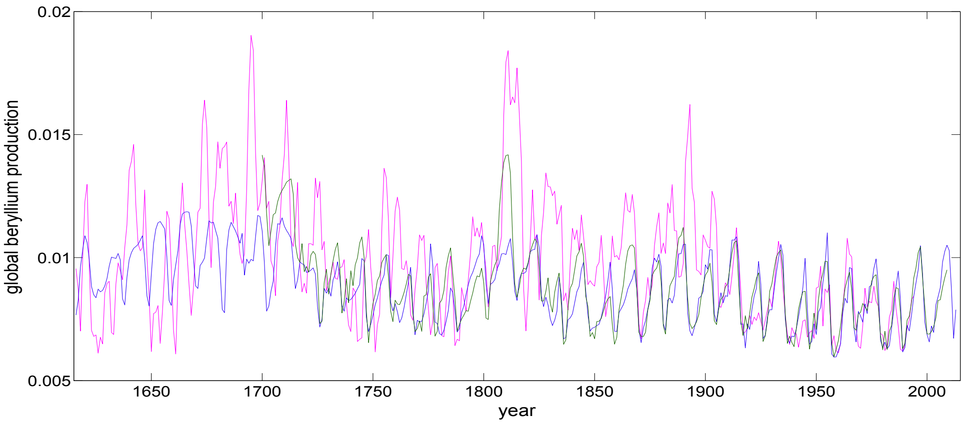

Figure 4: Annual variations of radionuclide ^{10}Be production and distribution modelled using the open solar magnetic flux estimated based on the Lockwood and Owens (2014); Lockwood et al. (2014) (blue curve), and on the Jiang et al. (2011) (green curve). Both reconstructions show a good agreement with the ^{10}Be records from terrestrial archives (Berggren et al. 2009) (magenta curve).

4. Centennial reconstructions

Using two different reconstructions of the OSMF, the one provided by Lockwood and Owens (2014); Lockwood et al. (2014) and the other by Jiang et al. (2011), we reconstruct the modulation potential for the period 1616-2013 and 1700-2009 respectively. These reconstructions were used to estimate the global production of radionuclides ^{14}C and ^{10}Be using the cosmogenic production models by Kovaltsov et al. (2012) and Kovaltsov and Usoskin (2010) respectively. The results are shown in figures 3 and 4. In the same figures, one can see the centennial variations of these radionuclides based on the terrestrial archives. The computed production of the radionuclides agrees well with the archives, even though there is a discrepancy in the computations based the Jiang et al. (2011) OSMF, during the periods 1700-1719 and 1804-1817, and is due to underestimation of the OSMF. In the case of ^{10}Be there is an excellent agreement between the records and the computed series during the current era, 1900-present.

5. Conclusions

In this paper we present two models, aiming to reconstruct the HCS tilt angle and the heliospheric modulation of GCRs in centennial scales. Concerning the HCS tilt angle model, it is a mathematical approach that successfully describes the cyclic behaviour of the HCS tilt angle and its dependence solely on the phase of the solar cycle. The modelled tilt angle shows an excellent agreement with the WSO observations, especially for the ascending phase of the solar cycle. Moreover it agrees well with reconstructions based on image analysis of total solar eclipses. This model can be, therefore, applied with the view of reconstructing the annual values of the tilt angle once the length of the solar cycle length is known. The main purpose of developing this model is to apply it for studying the heliospheric modulation of GCRs. The modulation model is a semi-empirical approach, describing the effects of the HCS and the HMF on the heliospheric transport of GCR particles. The modelled ϕ is in good agreement with the one reconstructed by ground based neutron monitor measurements. A small deviation appears during the latest solar maximum as well as the maximum of the 22nd solar cycle, with the latter being possibly related to high pressure of the solar wind plasma flow in conjunction with high plasma flow velocity. The global production of the radionuclides ^{14}C and ^{10}Be modelled using the modulation potential, reconstructed from the two different OSMF series, is in good agreement with the reconstructed values from tree rings and ice core records. More precisely, the modelled series show similar long-term trends with the records for both radionuclides. Regarding the ^{10}Be, the trend during the previous century is accurately described by the modelled series. Thus we conclude that the modulation model works well for long-term reconstructions.

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