A physical reconstruction of cosmic ray intensity since 1610

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[1]   The open solar magnetic flux has been recently reconstructed by *Solanki et al.* [2000, 2002] for the last 400 years from sunspot data. Using this reconstructed magnetic flux as an input to a spherically symmetric quasi-steady state model of the heliosphere, we calculate the expected intensity of galactic cosmic rays at the Earth's orbit since 1610. This new, physical reconstruction of the long-term cosmic ray intensity is in good agreement with the neutron monitor measurements during the last 50 years. Moreover, it resolves the problems related to previous reconstruction for the last 140 years based on linear correlations. We also calculate the flux of 2 GeV galactic protons and compare it to the cosmogenic ^{10}Be level in polar ice in Greenland and Antarctica. An excellent agreement between the calculated and measured levels is found over the last 400 years.   *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 1650 Global Change: Solar variability; 2162 Interplanetary Physics: Solar cycle variations (7536); *KEYWORDS:* cosmic rays, solar activity, Maunder minimum, heliosphere

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1.   Introduction

[2]   The era of in situ space measurements is short, only a few decades. On a longer timescale, models have to be used to reconstruct various solar/heliospheric parameters on the basis of indirect proxies. *Lockwood et al.* [1999] estimated the open solar magnetic flux for the last 140 years using geomagnetic activity. Recently *Solanki et al.* [2000, 2002] developed a method to reconstruct both the open and the total solar magnetic flux since 1700 from sunspot numbers.

[3]   In this paper we suggest a physical model for long-term cosmic ray calculation which is a combination of the solar magnetic flux model [*Solanki et al.*, 2000, 2002] and a spherically symmetric heliospheric model [*Gervasi et al.*, 1999; *Usoskin et al.*, 2002]. This combined model allows us to calculate the expected intensity of galactic cosmic rays (GCR) at the Earth's orbit for the last 400 years. We examine the performance of the model by comparing the model results, e.g., with the GCR data measured by the cosmogenic ^{10}Be level in polar ice. Since the value of the geomagnetic rigidity cutoff at a given location varies on a long timescale due to the changing orientation and intensity

of the geomagnetic dipole, we restrict our long-term analysis to polar regions only (Greenland, Antarctica, Northern Finland).

[4]   Section 2 presents the model to calculate the solar magnetic flux for the last 400 years. In sections 3 and 4 we discuss the heliospheric modulation of GCR and its relation to the solar magnetic flux. In section 5 we calculate the GCR intensity at 1 AU for the last 400 years both in the neutron monitor energy range and in the energy range of 2 GeV which is the most effective energy range for ^{10}Be production in the atmosphere. Section 6 gives the final discussion of results and the conclusions.

2.   Sunspot Activity and Open Solar Magnetic Flux

[5]   In their model of the solar magnetic flux, *Solanki et al.* [2000, 2002] used the Wolf sunspot series whose reliability before the early 19th century has been strongly questioned [*Sonett*, 1983; *Hoyt and Schatten*, 1999; *Letfus*, 1999; *Usoskin et al.*, 2001a]. In this work we use the group sunspot number series (Figure 1a) [*Hoyt and Schatten*, 1998] which is more consistent and homogeneous than the Wolf series for early times and allows us to deal with original (not interpolated or pre-processed) data. The group sunspot series
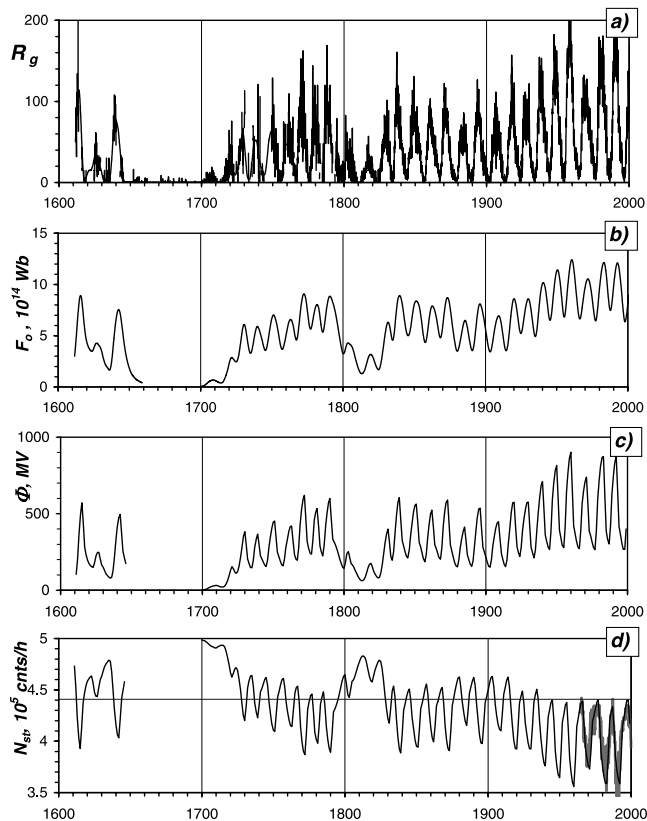
Figure 1. (a) Monthly group sunspot numbers. (b) The open solar magnetic flux F_o constructed by the method of *Solanki et al.* [2000] from the group sunspot number series. (c) The modulation strength Φ calculated from the open solar magnetic flux. (d) The reconstructed count rate of the standard neutron monitor for $P_c = 0.8$ GV. The actual Oulu NM count rate (scaled to the standard NM) is shown in grey for 1964–2000. The horizontal dotted line denotes the highest actually recorded NM count rate in May 1965.

contains several gaps, the longest gap being 27 months in the 1740s. Data have been interpolated over the gaps using a binomial interpolation in a 41-month window. It has been shown that using this interpolation the errors remain below 10% even for the longest gaps [*Usoskin et al*, 2000]. Note that these gaps are linearly interpolated, without an explicit note, in the Wolf sunspot series.

[6] Using the numerical recipe of *Solanki et al.* [2000] and the group sunspot number series we have calculated the open solar magnetic flux F_o since 1610 as shown in Figure 1b. The two series, as calculated from group sunspot and Wolf sunspot numbers (see Figure 2 by *Solanki et al.* [2000]), are almost identical with each other for the period after 1870 but deviate significantly (by several tens of percent) in early 18th century due to the difference between the two sunspot series. As discussed later, the present model using group sunspot series gives a better agreement with the cosmic ray data. The reconstruction is not possible during the deep Maunder minimum in 1645–1699 because of extremely sparse sunspot activity. However, since the sunspot activity was fairly high and regular even before the Maunder minimum, we calculated the magnetic flux also for that period. Note that in

the period 1860–1999 the open solar magnetic flux reconstructed from the Solanki model also agrees fairly well with the reconstruction of *Lockwood et al.* [1999].

3. Heliospheric Modulation of Cosmic Rays

[7] Heliospheric transport of GCR is described by Parker's transport equation [*Parker*, 1965] which can be written in a spherically symmetric and steady state form as

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\kappa\frac{\partial U}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2VU\right) + \frac{1}{3}\cdot\left(\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2V\right)\right)$$
$$\cdot\left(\frac{\partial}{\partial T}(\alpha TU)\right) = 0 \qquad (1)$$

where $U(r,T)$ is the cosmic ray number density per unit interval of kinetic energy T, r is the heliocentric distance, V is the solar wind speed, $\alpha = (T + 2 \cdot T_r)/(T + T_r)$, T_r is proton's rest energy and κ is the diffusion coefficient. It is usual to take the diffusion coefficient in the following form [see, e.g., *Perko*, 1987]

$$\kappa = \kappa_o \cdot \beta P, \qquad P > P_b$$
$$\kappa = \kappa_o \cdot \beta P_b, \qquad P < P_b \qquad (2)$$

where $\beta = v/c$, v and P are the velocity and rigidity of a cosmic ray particle ($P_b = 1$ GV).

[8] Under some simplifying assumptions which are valid if

$$\frac{r}{U}\frac{\partial U}{\partial r} \ll 1. \qquad (3)$$

the basic transport equation (1) can be reduced to the so-called force-field approximation form [*Gleeson and Axford*, 1968; *Fisk and Axford*, 1969]:

$$\frac{\partial U}{\partial r} + \frac{VP}{3\kappa}\frac{\partial U}{\partial P} = 0 \qquad (4)$$
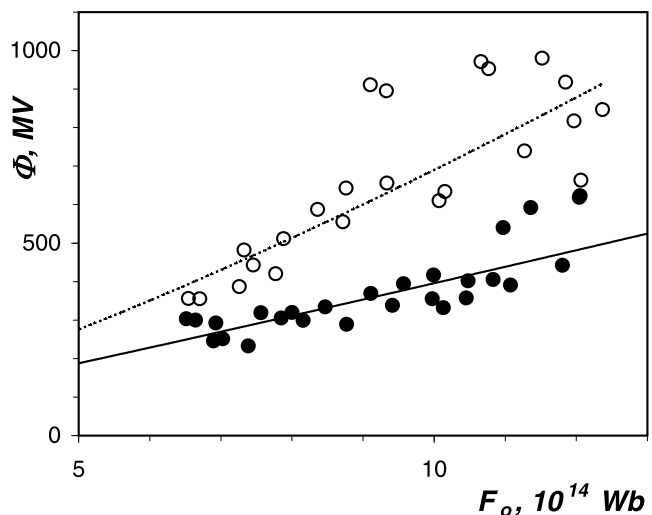

Figure 2. Scatterplot between the annual (1951–2000) modulation strength Φ as taken from *Usoskin et al.* [2002] and the calculated solar open magnetic flux. Filled (open) circles correspond to the ascending (descending) phase of solar activity. The corresponding best fits of Equations (9) and (10) are depicted by solid (dotted) lines.

The equation (4) can be solved analytically in the form of characteristic curves. This approach has been used earlier to study heliospheric modulation of GCR on the long timescale [see, e.g., *O'Brien and de Burke*, 1973; *Masarik and Beer*, 1999]. However, although the force-field approximation is good for weak heliospheric modulation and in the outer heliosphere, it overestimates the differential flux of low-energy cosmic rays at a strong modulation level because the condition (3) breaks there [*Usoskin et al.*, 2002].

[9] In this study we make use of a spherically symmetric quasi-steady stochastic simulation model of the heliosphere described in detail elsewhere [*Gervasi et al.*, 1999; *Usoskin et al.*, 2002]. This model solves numerically the transport equation (1) using the stochastic simulation method and tracing test particles in the heliosphere. It has been shown recently [*Usoskin et al.*, 2002] that this method reliably describes the long-term modulation of cosmic rays during the last 50 years, giving correct estimates for both integral intensities and differential energy spectra.

[10] The most important parameter of the heliospheric modulation of GCR in 1D is the so-called modulation strength [*Gleeson and Axford*, 1968] which is the only parameter in the force-field approximation (Equation 4)

$$\Phi = \int_{r_E}^{D} \frac{V}{3\kappa_o} dr = \frac{(D - r_E)V}{3\kappa_o}, \tag{5}$$

where D is the heliospheric boundary (termination shock) and $r_E = 1$ AU. Although the solar wind is important for heliospheric modulation, the direct correlation between the solar wind speed and the cosmic ray variations is quite weak [see, e.g., *Belov*, 2000]. Therefore, we assume a constant solar wind speed at 400 km/s. We note that the position of the termination shock may vary in time [*Webber and Lockwood*, 1987; *Exarhos and Moussas*, 2001]. However, the effect of the varying heliospheric size on GCR intensity at 1 AU was recently estimated to be small during the last 50 years [*Exarhos and Moussas*, 2001]. Therefore we take the heliospheric size to be fixed at $D = 100$ AU in our model. Thus, all changes in the modulation strength Φ in our model are related to the changing diffusion coefficient κ_o.

[11] Using the stochastic simulation model, we calculate the differential intensity of cosmic rays at the Earth's orbit $G(P, \Phi)$ for different values of the modulation strength Φ. The model adopts the following local interstellar spectrum of GCR (i.e., outside the heliosphere) as a function of rigidity [*Burger et al.*, 2000]:

$$G_{LIS}(P) = 1.9 \cdot 10^4 P^{-2.78}, \quad P \geq 7 GV$$

$$G_{LIS}(P) = exp\left(9.472 - 1.999 \cdot lnP - 0.6938(lnP)^2 + 0.2988(lnP)^3\right.$$
$$\left. - 0.04714(lnP)^4\right), \quad P < 7 GV \tag{6}$$

where P is expressed in GV, and G_{LIS} in given in (GeV sr m^2 s)$^{-1}$. Note that there is an error in formula (2) of *Burger et al.* [2000] which is corrected in Equation (6) (Burger and Potgieter, personal communication, 2001). Then the response of a neutron monitor (NM) to cosmic rays (the count rate) was calculated as

$$N(P_c, x, \Phi) = \int_{P_c}^{\infty} G(P, \Phi) \cdot Y(P, x) \cdot dP, \tag{7}$$

where x and P_c are the atmospheric depth and the geomagnetic rigidity cutoff of the NM location, and $Y(P, x)$ is the specific yield function which accounts for the propagation of GCR particles in the Earth's atmosphere and the detection of secondary nucleons [*Clem and Dorman*, 2000]. Here we use the specific yield function $Y(P)$ as presented by *Debrunner et al.* [1982] and modified in the high rigidity part by *Nagashima et al.* [1989].

4. Modulation Strength Versus Solar Magnetic Flux

[12] The diffusion coefficient κ depends inversely on the interplanetary magnetic field (IMF) strength B because of a stronger scattering of cosmic ray particles in an enhanced magnetic field [*Chin and Lee*, 1986; *Potgieter et al.*, 2001; *Wibberenz et al.*, 2001]. On the other hand, the open solar magnetic flux is by definition proportional to the average IMF strength at a fixed distance to the Sun. Therefore, we expect the following rough relation between the modulation strength and solar magnetic flux:

$$\Phi(t) \propto F_o^{\alpha} \tag{8}$$

According to the expected functional form (Equation 8), we study the relationship between the modulation strength Φ estimated recently for the neutron monitor era of 1951–2000 [*Usoskin et al.*, 2002] and the solar open magnetic flux F_o calculated from group sunspot numbers for the same years. The scatterplot of annual values of Φ vs. F_o is shown in Figure 2. Although the correlation is significant (cross-correlation coefficient $R = 0.64$), the scatterplot is not homogeneous. The relation (8) is 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., *Belov*, 2000; *Boella et al.*, 2001]. Therefore, we fit the functional relation (Equation (8)) separately for the ascending

$$\Phi_{as} = 49.6 \cdot F_o^{0.9} \tag{9}$$

and descending phase

$$\Phi_{des} = 44.2 \cdot F_o^{1.2}, \tag{10}$$

where Φ and F_o are given in MV and 10^{14} Wb, respectively. We note that this hysteresis effect is only important on timescales shorter than 11-year cycle, and disappears on longer timescales.

[13] In order to illustrate our method, we have calculated, starting from the measured group sunspot numbers, the open solar magnetic flux F_o for the neutron monitor era, 1951–2001. Then, we calculated the modulation strength Φ using Equations (9) and (10), and the expected count rate of a standard NM using Equation 7. (As the standard NM we assume a 1-NM-64 neutron monitor at sea level). The expected count rates (for $P_c = 3$ GV, corresponding to the Climax NM) are compared with the observed count rates of the Climax NM for 1951–2001 in Figure 3. A good agreement is obtained (R ≈ 0.91). However, some differences between the two curves exist during specific periods. In 1989–1991, a series of huge Forbush decreases took place, leading to a reduced GCR level and a distorted phase
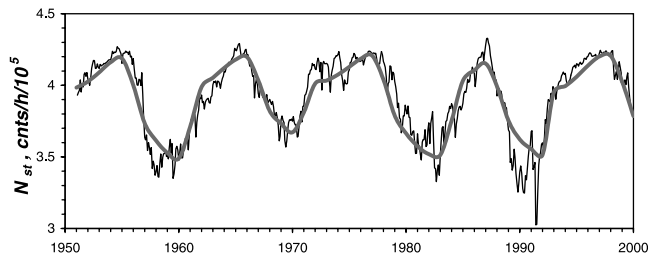
Figure 3. The actual Climax NM count rates (thin curve) and the one predicted by the model from the group sunspot numbers (thick grey curve).

evolution of the GCR cycle [*Usoskin et al.*, 1998]. A similar situation occurred also in 1958 and in 1982. Also, the so-called GCR minicycle in 1972–1974 with unusual features in the global solar magnetic field and heliospheric structure [*Benevolenskaya*, 1998; *Wibberenz et al.*, 2001] is not reproduced by the model, although the model gives a reasonable average value of the cosmic ray flux for this period. Accordingly, we conclude that our method reproduces the average cosmic ray intensity with good accuracy, while some specific features caused, e.g., by strong transient phenomena or unusual heliospheric structures are neglected by the method.

5. Reconstruction of Cosmic Ray Flux

5.1. Neutron Monitor Count Rate

[14] Using Equations (9) and (10) we have calculated the modulation strength Φ for the last four centuries (Figure 1c) from the open solar magnetic flux F_o (Figure 1b). Note the large variations of Φ even during the last 200 years with a minimum of about 100 MV during the Dalton minimum and a maximum of about 900 MV during recent solar maxima.

[15] Note also that, since the model of *Solanki et al.* [2000] is based upon sunspot activity, the magnetic flux approaches to 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 [*Cliver et al.*, 1998; *Usoskin et al.*, 2001b]. Therefore, an exact reconstruction of Φ during the Maunder minimum is not possible on the basis of this method.

[16] From this calculated modulation strength, we have calculated the reconstructed response of the standard NM to GCR variations for the entire nearly 400-year interval (Figure 1d), using Equation (7). In this Figure we have used a polar neutron monitor ($P_c = 0.8$ GV, corresponding to Oulu, Finland) and depicted the model results for the last four centuries together with the actual Oulu NM count rates for 1964–2000.

[17] The reconstructed GCR series depicted in Figure 1d 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 [*Ahluwalia*, 2000; *Stozhkov et al.*, 2000]. However, this trend is not persistent throughout the entire 400-year interval, contrary to the suggestion by *Stozhkov et al.* [2000] who interpreted the trend in terms of a possible supernova explosion in the vicinity of the solar system.

[18] Note that our reconstructed GCR intensity (Figure 1d) greatly differs from that by *Lockwood* [2001] for the last 140 years. As discussed recently [*Mursula et al.*, 2002]

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 Figure 1d) around 1900. However, it has been estimated from various indirect proxies that the GCR intensity was well below LIS at that time [*O'Brien et al.*, 1991; *Bonino et al.*, 2001; *McCracken*, 2001; *Scherer et al.*, 2001]. Our model agrees with these estimates, predicting that the GCR intensity was indeed significantly below LIS around 1900.

5.2. Cosmogenic Isotope ^{10}Be

[19] Interaction of GCR particles with oxygen and nitrogen nuclei of the Earth's atmosphere results in the production of ^{10}Be radionuclides which, after precipitation on aerosols, are stored in the natural archive of polar ice for a long time [*Beer et al.*, 1990]. The mean energy of GCR needed to produce ^{10}Be in the atmosphere is about 2 GeV [*Masarik and Beer*, 1999; *McCracken*, 2001]. Not going into the details of atmospheric transport of ^{10}Be [*McHargue and Damon*, 1991], we assume that the production rate and the ensuing ^{10}Be level are directly proportional to the flux of cosmic ray particles with energy around 2 GeV. The calculated flux of 2 GeV cosmic rays was then scaled to adjust to the average level of the ^{10}Be abundance in Greenland ice during the last 400 years [*Beer et al.*, 1990]. The annual values of the reconstructed flux are shown in Figure 4a together with the two ^{10}Be data sets: the annual ^{10}Be abundance measured in Greenland ice [*Beer et al.*, 1990] and the roughly 8-year ^{10}Be data from Antarctica [*Bard et al.*, 1997]. The cross-correlation coefficient between the actual and reconstructed annual ^{10}Be series is $R \approx 0.6$.

[20] The model reproduces the long-term trend even better. Figure 4b depicts the 11-year averages of the model flux and the Greenland series. The cross-corellation between these two series is $R \approx 0.86$. The cross-correlation between the model flux and the Antarctic 8-year series is $R \approx 0.84$. Note also that a slightly lower correlation of about 0.78(0.70) is found between the model and averaged Greenland (Antarctic) series if Wolf sunspot numbers are used instead of the group sunspot numbers.

[21] There are two periods when the reconstructed and the measured 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 19th century, respectively [see, e.g., *Fischer et al.*, 1998; *Cubasch and Voss*, 2000, and references therein]. Local climatic effects are known to play a role in the deposition of ^{10}Be in polar ice [*Lal*, 1987; *Beer et al.*, 1990]. Therefore, the differences between the model and the measured records may be related to significant variations of climatic conditions and resulting changes in the ^{10}Be deposition during these periods.

6. Discussion and Conclusions

[22] In this paper we have reconstructed the cosmic ray intensity for the last 400 years (Figure 1d) using, for the first time, a physical rather than a phenomenological model. First, we calculated the open solar magnetic flux (see Figure
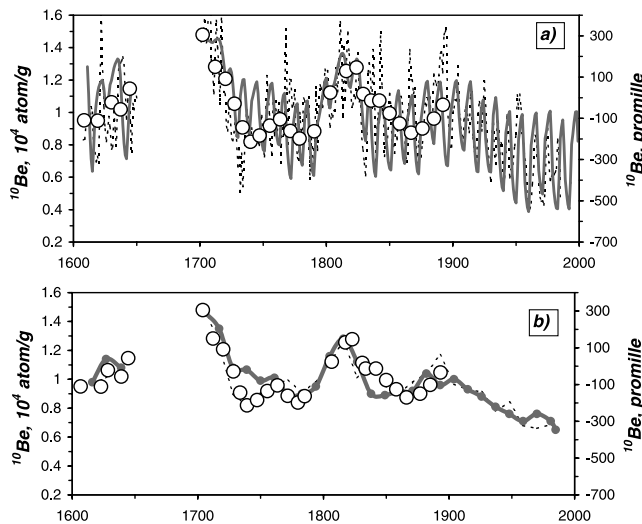
Figure 4. (a) Annual series of ^{10}Be abundance in polar ice in Greenland (dashed line) and the model GCR flux (solid line). Big dots and right axis correspond to the Antarctic ^{10}Be series. (b) The 11-year smoothed curves.

1b) from group sunspot number series (Figure 1a) using a recent model by *Solanki et al.* [2000, 2002]. This open magnetic flux was then used as an input for a heliospheric model [*Gervasi et al.*, 1999; *Usoskin et al.*, 2002] to calculate the cosmic ray intensity. This heliospheric model is spherically symmetric and quasi steady, corresponding to the diffusion-convection dominated propagation of GCR in the heliosphere. Using the stochastic simulation technique to numerically solve the one-dimensional transport equation (Equation 1), the model describes the heliospheric modulation better than the earlier used force-field approximation [*Usoskin et al.*, 2002]. On the other hand, the model does not take into account non-spherical (e.g., drifts) or non-steady effects (e.g., interaction regions). However, these effects are important mostly on short timescales. We also note that more sophisticated models cannot be used on long time scales since their numerous parameters cannot be fitted with a single time series of the open magnetic flux.

[23] The excellent long-term agreement between the model flux of 2 GeV protons and the measured level of ^{10}Be content in polar ice (Figure 4) supports the model described and applied here. The agreement is weaker, as expected, on shorter timescales of a couple of years because other effects (climatic, atmospheric, etc.) play a significant role in ^{10}Be deposition on short timescales.

[24] We found that our model gives a slightly better agreement with the measured ^{10}Be data if group sunspot numbers are used (as done here) in the model by *Solanki et al.* [2000, 2002] rather than the Wolf sunspot numbers. This supports the claim that group sunspot numbers are more consistent in the early years than the Wolf series [*Hoyt and Schatten*, 1998; *Letfus*, 1999].

[25] We also note that the present results, while being in accordance with the measured indirect proxies around 1900, deviate significantly from those given recently by *Lockwood* [2001] for the last 140 years. It is important that Lockwood only used empirical linear correlations, while the

present model based on physical principles is essentially non-linear.

References

Ahluwalia, H. S., On galactic cosmic ray flux decrease near solar minima and IMF intensity, *Geophys. Res. Lett.*, *27*, 1603–1606, 2000.

Bard, E., G. M. Raisbek, F. Yiou, and J. Jouzel, Solar modulation of cosmogenic nuclide production over the last millenium: Comparison between ^{14}C and ^{10}Be records, *Earth Planet. Sci. Lett.*, *150*, 453–462, 1997.

Beer, J., A. Blinov, and G. Bonani, et al., Use of ^{10}Be in polar ice to trace the 11-year cycle of solar activity, *Nature*, *347*, 164–166, 1990.

Belov, A. V., Large scale modulation: View from the Earth, *Space Sci. Rev.*, *93*, 79–105, 2000.

Benevolenskaya, E. E., Longitudinal Structure of the Double Magnetic Cycle, *Sol. Phys.*, *181*, 479–489, 1998.

Boella, G., M. Gervasi, S. Mariani, P. G. Rancoita, and I. G. Usoskin, Evidence for charge drift modulation at intermediate solar activity from the flux variation of protons and alpha particles, *J. Geophys. Res.*, *106*, 29,355–29,362, 2001.

Bonino, G., G. Cini Castagnoli, D. Cane, C. Taricco, and N. Bhandari, Solar modulation of the galactic cosmic ray spectra since the Maunder minimum, *Proc. Int. Conf. Cosmic Rays*, *27th*, 3762–3769, 2001.

Burger, R. A., M. S. Potgieter, and B. Heber, Rigidity dependence of cosmic ray proton latitudinal gradients measured by the Ulysses spacecraft: Implication for the diffusion tensor, *J. Geophys. Res.*, *105*, 27,447–27,455, 2000.

Chin, P. P., and M. A. Lee, A perturbation approach to cosmic ray transients in interplanetary space, *J. Geophys. Res.*, *91*, 2903–2913, 1986.

Clem, J. M., and L. I. Dorman, Neutron monitor response functions, *Space Sci. Rev.*, *93*, 335–359, 2000.

Cliver, E. W., V. Boriakoff, and K. H. Bounar, Geomagnetic activity and the solar wind during the Maunder minimum, *Geophys. Res. Lett.*, *25*, 897–900, 1998.

Cubasch, U., and R. Voss, The influence of total solar irradiance on climate, *Space Sci. Rev.*, *94*, 185–198, 2000.

Debrunner, H., E. Flueckiger, J. A. Lockwood, 8th Eur. Cosmic Ray Symp., Rome, 1982.

Exarhos, G., and X. Moussas, Simulation of the temporal variations of the galactic cosmic-ray intensity at neutron monitor energies, *Sol. Phys.*, *200*, 283–292, 2001.

Fischer, H., et al., Little ice age clearly recorded in northern Greenland ice cores, *Geophys. Res. Lett.*, *25*, 1749–1752, 1998.

Fisk, L. A., and W. I. Axford, Solar modulation of galactic cosmic rays, 1, *J. Geophys. Res.*, *74*, 4973–4986, 1969.

Gervasi, M., P. G. Rancoita, I. G. Usoskin, and G. A. Kovaltsov, Monte-Carlo approach to Galactic Cosmic Ray propagation in the Heliosphere, *Nucl. Phys. B, Proc. Suppl.*, *78*, 26–31, 1999.

Gleeson, L. J., and W. I. Axford, Solar modulation of galactic cosmic rays, *Astrophys. J.*, *154*, 1011–1026, 1968.

Hoyt, D. V., and K. Schatten, Group sunspot numbers: A new solar activity reconstruction, *Sol. Phys.*, *179*, 189–219, 1998.

Lal, D., ^{10}Be in polar ice: Data reflect changes in cosmic ray flux or polar meteorology, *Geophys. Res. Lett.*, *14*, 785–788, 1987.

Letfus, V., Daily relative sunspot numbers 1749–1848: Reconstruction of missing observations, *Sol. Phys.*, *184*, 201–211, 1999.

Lockwood, M., Long-term variations in the magnetic field of the Sun and the heliosphere: The origin, effects and implications, *J. Geophys. Res.*, *106*, 16,021–16,038, 2001.

Lockwood, M., R. Stamper, and M. N. Wild, A doubling of the Sun's coronal magnetic field during the past 100 years, *Nature*, *399*, 437–439, 1999.

Masarik, J., and J. Beer, Simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere, *J. Geophys. Res.*, *104*(D10), 12,099–12,111, 1999.

McCracken, K. G., Variations in the production of ^{10}Be due to the 11 year modulation of the cosmic radiation, and variations in the vector geomagnetic dipole, *Proc. Int. Conf. Cosmic Ray*, *27th*, 4129–4132, 2001.

McHargue, L. R., and P. E. Damon, The global Beryllium 10 cycle, *Rev. Geophys.*, *29*, 141–158, 1991.

Mursula, K., I. G. Usoskin, and G. A. Kovaltsov, Reconstructing the long-term cosmic ray intensity: Linear relations do not work, *Annal. Geophys.*, in press, 2002.

Nagashima, K., S. Sakakibara, K. Murakami, and I. Morishita, Response and yield functions of neutron monitor, Galactic cosmic ray spectrum and its solar modulation, derived from all the available world-wide surveys, *Nuovo Cimento*, *12*(C2), 173–209, 1989.

O'Brien, K., and G. P. de Burke, Calculated cosmic ray neutron monitor response to solar modulation of galactic cosmic rays, *J. Geophys. Res.*, *78*, 3013–3019, 1973.

O'Brien, K., A. De La Zerda Lerner, M. A. Shea, and D. F. Smart, The production of cosmogenic isotopes in the Earth's atmosphere and their inventories, in *The Sun in Time*, edited by C. P. Sonnet, M. S. Giampapa, and M. S. Matthews, pp. 317–343, Univ. of Ariz., Tucson, 1991.

Parker, E. N., The passage of energetic charged particles through interplanetary space, *Planet. Space Sci.*, *13*, 9, 1965.

Perko, J. S., Solar modulation of galactic antiprotons, *Astron. Astrophys.*, *184*, 119–121, 1987.

Potgieter, M., R. A. Burger, and S. E. S. Ferreira, Modulation of cosmic rays from solar minimum to maximum: A theoretical respective, *Space Sci. Rev.*, *97*, 295–307, 2001.

Scherer, K., H. Fichtner, O. Stawicki, and H. J. Fahr, Cosmogenic element production in meteorites - The influence of long-term variation in heliospheric structure, *Proc. Int. Conf. Cosmic Ray*, *27th*, 4031–4034, 2001.

Solanki, S. K., M. Schüssler, and M. Fligge, Evolution of the Sun's large-scale magnetic field since the Maunder minimum, *Nature*, *408*, 445–447, 2000.

Solanki, S. K., M. Schüssler, and M. Fligge, Secular variations of the Sun's magnetic field, *Astron. Astrophys.*, *383*, 706–712, 2002.

Sonett, C. P., The great solar anomaly ca. 1780–1800 - an error in compiling the record, *J. Geophys. Res.*, *88*, 3225–3228, 1983.

Stozhkov, Y. I., P. E. Pokrevsky, and V. P. Okhlopkov, Long-term negative trend in cosmic ray flux, *J. Geophys. Res.*, *105*, 9–17, 2000.

Usoskin, I. G., H. Kananen, G. A. Kovaltsov, K. Mursula, and P. Tanskanen, Correlative study of solar activity and cosmic ray intensity, *J. Geophys. Res.*, *103*, 9567–9574, 1998.

Usoskin, I. G., K. Mursula, and G. A. Kovaltsov, Sunspot activity during the Maunder minimum, *Astron. Astrophys.*, *354*, L33–L36, 2000.

Usoskin, I. G., K. Mursula, and G. A. Kovaltsov, Was one sunspot cycle lost in late XVIII century?, *Astron. Astrophys.*, *370*, L31–L34, 2001a.

Usoskin, I. G., K. Mursula, and G. A. Kovaltsov, Heliospheric modulation of cosmic rays and solar activity during the Maunder minimum, *J. Geophys. Res.*, *106*, 16,039–16,045, 2001b.

Usoskin, I. G., K. Alanko, K. Mursula, and G. A. Kovaltsov, Heliospheric modulation strength during the neutron monitor era, *Sol. Phys.*, *207*, 389–399, 2002.

Webber, W. R., and J. A. Lockwood, Interplanetary radial cosmic-ray gradients and their implication for a possible large modulation effect at the heliospheric boundary, *Astrophys. J.*, *317*, 534–542, 1987.

Wibberenz, G., S. E. S. Ferreira, M. S. Potgieter, and H. V. Cane, Time-dependent 2D model compared with observations during the 1974 mini cycle, *Space Sci. Rev.*, *97*, 373–376, 2001.

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