Heliospheric Modulation over the past 10,000 Years as derived from Co smogenic Nuclides

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Abstract

Neutron monitors have recorded variations in cosmic rays with high precision and high temporal resolution for the past 50 years. However, sunspots and other solar proxies indicate that larger changes in heliospheric modulation are to be expected over longer time scales. Cosmogenic radionuclides provide a tool to extend the neutron monitor records to at least 10,000 years, but with a much coarser temporal resolution (>1 y) and a lower signal to noise ratio. Using the ^{10}Be record from the GISP2 ice core it is shown how the geomagnetic modulation component is removed, and the remaining ^{10}Be signal interpreted in terms of the heliospheric modulation parameter Φ.

1. Introduction

Neutron monitors have been in operation for about 50 years worldwide and have provided a wealth of information on the galactic cosmic rays and heliospheric modulation. This limited period means that only short-term processes have been studied to date. However, sunspot and auroral data indicate that solar activity has undergone large changes on longer time scales than experienced during the past 50 yrs. This raises the question as to how the GCR changed at these times and especially during intervals such as the Maunder minimum (1645-1715 AD).

The only way to extend the neutron monitor records to much earlier times is to rely on a special type of neutron monitor, the cosmogenic nuclides [1]. In a very general sense cosmogenic nuclides can be considered as neutron monitors with a low temporal resolution (>1 year) and a low signal to noise ratio, but with the big advantage of covering at least the past 10,000 years.

2. Methods

Cosmogenic nuclides such as ^{10}Be, ^{14}C, and ^{36}Cl are produced mainly by high-energy neutrons (^{14}C: thermal neutrons) interacting with nitrogen, oxygen,

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and argon within the atmosphere. Rather than counting the number of nuclear reactions, the amount of cosmogenic nuclides produced is determined. This is possible because these nuclides are eventually removed from the atmosphere and some of them are stored in natural archives such as ice sheets or tree rings where they can be found and counted thousands of years later. The half-lives of the three nuclides are 1.5 x 10^6, 5730 and 301,000 years respectively, allowing investigation of the GCR variability over long periods of time. Since, on average, it takes 1-2 years for ^{10}Be and ^{36}Cl and considerably longer for ^{14}C to be stored in such an archive, the time resolution of this cosmogenic neutron monitor is limited accordingly.

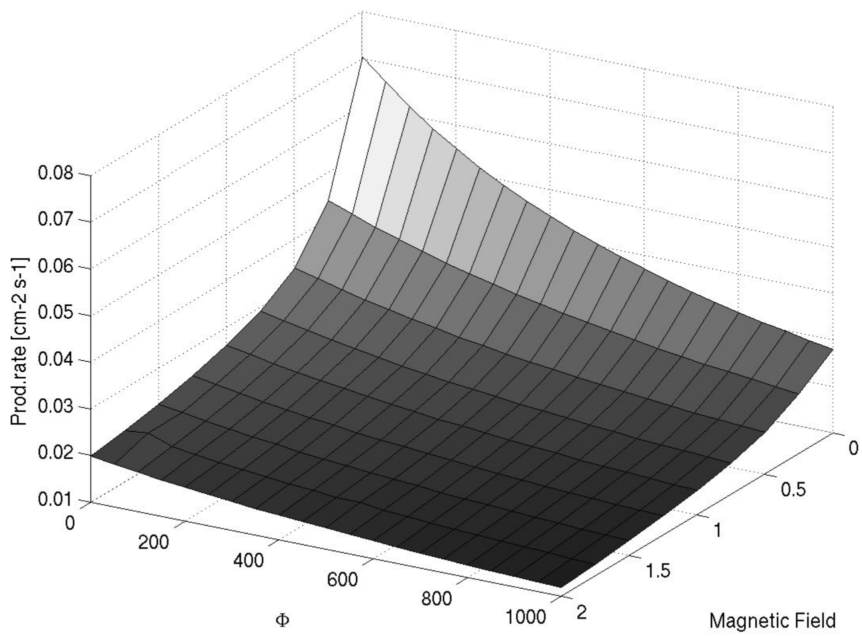

Fig. 1. Dependence of the mean global ^{10}Be production rate on the solar activity Φ and the geomagnetic field intensity (rel. units; 1: present field) [2]. The dynamic range between high solar activity / large magnetic field and quiet sun / no field is about an order of magnitude.

The transport from the atmosphere into the archive is not only responsible for the low temporal resolution. It also generates noise because of the many processes involved and their dependence on the prevailing atmospheric and metrological conditions (general transport; air exchange between stratosphere and troposphere; removing of ^{10}Be and ^{36}Cl attached to aerosols from the atmosphere by wet and dry deposition; fluctuations within the carbon cycle in the case of ^{14}C). However, under stable climatic conditions the flux of cosmogenic radionuclides from the atmosphere into an ice sheet can be considered as proportional to the production rate. Calculations show that the maximum of the ^{10}Be yield function ranges between 1-2 GeV/nucleon [3,4]. Extensive simulations of the atmospheric neutron and proton spectra for different levels of solar activity expressed by the modulation parameter Φ, and different geomagnetic dipole moments, have revealed how the production rate depends on magnetic dipole moment and solar activity (Fig. 1) [2].

3. Results and Discussion

For the cosmogenic nuclides to become a really useful tool in cosmic ray physics that can detect the heliospheric modulation signal, it is necessary to show that production and system effects can be separated, and that the noise level is low enough. This has been done by showing that ^{10}Be records reveal clearly the 11-y Schwabe cycle [5] and solar minima such as the Maunder minimum [6]. The fact that ^{10}Be and ^{14}C records are very similar in spite of their fundamentally different geochemical systems is further evidence that the cosmogenic nuclides primarily reflect production and not system effects, at least during the Holocene (the last 10,000 years) [7,8].

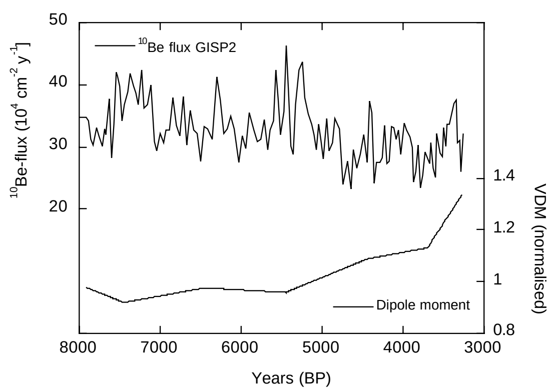

Fig. 2. ^{10}Be flux from the GISP2 ice core [9] and the geomagnetic dipole moment (units relative to today) [10].

For this reason, the 10Be flux record from Greenland during a non-glacial period (eg, the last 12,000 years) can be interpreted as a record of the heliospheric and geomagnetic modulation of the GCR. To illustrate the extraction of the heliospheric modulation we choose the ^{10}Be flux from the GISP2 ice core [2] covering the period 8000 to almost 3000 years before present (present being 1950) (Fig. 2). In order to reconstruct the heliospheric modulation, we first remove the effects of the changing geomagnetic dipole, using a time dependence based on a large number of archeomagnetic measurements [10] (Fig. 2 lower panel). Φ was then derived using the relationship between ^{10}Be production rate, geomagnetic dipole moment (M) and solar modulation (Φ) shown in Fig. 1. Fig. 3

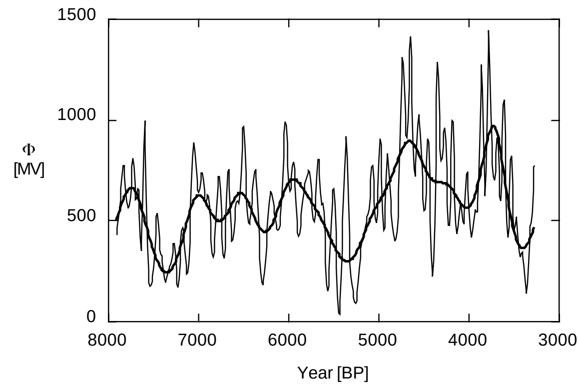

Fig. 3. Solar modulation parameter Φ as derived from the ^{10}Be record (Fig. 2) filtered with 50 years (thin curve) and 500 years (thick curve) low pass filters.

displays the results after applying low pass filters with cut-off periodicities of 50 and 500 years. The calculations show that Φ extended over the range 0-1500 MV, compared to an average Φ since 1950 of $\sim$800 MV, and that there were distinct periods with higher and lower cosmic ray modulation than the present. Spectral analysis reveals the 88 y (Gleissberg) and 208 (Suess or DeVries) periodicities, and others.

In conclusion this example shows that cosmogenic radionuclides have the potential to reconstruct the solar modulation parameter Φ over the past 10 millennia. The changes in Φ were much larger in earlier times than experienced during the instrumental period. Careful comparison of ^{10}Be and ^{36}Cl records from different ice cores with the ^{14}C tree ring record will eventually improve the temporal resolution to 1-2 years, reduce the noise, and provide a means to estimate the uncertainties.

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4. References

1. Beer, J., Space Science Rev., 2000. 93: p. 107.
2. Masarik, J. and J. Beer, J. Geophys. Res., 1999. 104(D10): p. 12,099.
3. Usoskin, I. et al., J. Geophys. Res., 2001. 106(A8): p. 16039.
4. McCracken, K.G. in ICRC 2001. 2001. Copernicus Gesellschaft: p. 4129.
5. Beer, J., et al., Nature, 1990. 347(6289): p. 164-166.
6. Beer, J., et al., in Sun in Time. 1991, Univ. of Arizona press: Tucson. p. 343.
7. Beer, J., et al., in The solar engine and its influence on terrestrial atmosphere and climate, E. Nesme-Ribes, Editor. 1994, Springer-Verlag: p. 221.
8. Muscheler, R., et al., Nature, 2000. 408: p. 567.
9. Finkel, R.C. and K. Nishiizumi,. J. Geophys. Res., 1997. 102(C12): p. 26699.
10. Yang, S., et al., Geophys. J. Int., 2000. 140: p. 158.