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Production of cosmogenic Be nuclei in the Earth's atmosphere by cosmic rays: Its dependence on solar modulation and the interstellar cosmic ray spectrum

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[1] Recent work by *McCracken* [2001] shows that ^{10}Be production rates by cosmic rays on the polar plateau are little affected by geomagnetic field changes in the last few hundred years. Also, the ^{10}Be observed in ice cores on the polar plateau probably originated at high latitudes and precipitated to the Earth in about 1 year, according to McCracken. As a result of this assumption, ice core records of ^{10}Be concentration extending back several hundred years, including the Maunder minimum, have the potential to study the solar modulation of cosmic rays on a time scale extending back several hundred years. These ice core records indicate that the ^{10}Be concentration at the time of the Maunder minimum was ~2.0 times what it was during recent sunspot minima in 1965 and 1976. We have examined ^{10}Be production in the atmosphere using new data related to the interstellar cosmic ray spectrum and the effects of solar modulation as determined from Voyager spacecraft data in the outer heliosphere. We have used the FLUKA Monte Carlo program along with new cross-section data to calculate the production of nucleons and ^{10}Be nuclei in the atmosphere. These calculations show that ^{10}Be temporal variations are sensitive indicators of low-energy solar modulation. Our calculations of ^{10}Be production are able to reproduce well the factor ~1.5–2.0 change in ^{10}Be observed in the ice core data as a result of the 11-year solar modulation. We are also able to show that starting as recently as the sunspot minimum of 1954, the cosmic ray intensity at the Earth was higher than it was during more recent minima. The cosmic ray intensity during these minima time periods represents the residual modulation between the Earth and interstellar space. The ^{10}Be measurements are consistant with the fact that given the interstellar cosmic ray spectrum used in this analysis, this residual modulation was small or zero at the time of the Maunder minimum. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 2124 Interplanetary Physics: Heliopause and solar wind termination; 2162 Interplanetary Physics: Solar cycle variations (7536); 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); *KEYWORDS:* cosmogenic nuclei, cosmic rays, protons, nuclear cross sections, heliosphere, solar cycle

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1. Introduction

[2] The interactions of cosmic ray protons and heavier nuclei with the Earth's atmosphere produce a cascade of secondary nucleons. These primaries, as well as the secondaries nucleons produced, result in the production of several interesting cosmogenic radionuclides such as ^{7}Be, ^{10}Be, and ^{14}C. The development of accelerator mass spectrometry (AMS) has increased the detection sensitivity for these cosmogenic radionuclides by several orders of magnitude, thus allowing the analysis with high time resolution of the abundance of these nuclides in natural archives such as ice cores. The concentration of these nuclides is the result of the combination of production, transport and disposition in the Earth's atmosphere. The production rate of the cosmogenic nuclides depends primarily on the cosmic ray particle flux at the top of the Earth's atmosphere. Time-dependent changes in this production rate are caused by the solar modulation of the galactic cosmic rays which is related to solar activity and also by variations in the geomagnetic field and by atmospheric mixing processes.

[3] Solar modulation related to the 11-year and longer solar cycles is a dominant cause of galactic cosmic ray variability at the Earth. During a typical 11-year solar cycle the variation of 1 GeV protons is about a factor of 5 and is smaller at higher energies and larger at lower energies, generally following an energy dependence $\sim E^{-1}$. This

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modulation is the result of the interaction of the incoming galactic cosmic rays with the outwardly convected solar magnetic fields and plasma in the heliosphere out to ~100 AU and beyond.

[4] The geomagnetic field, which is dominated by its dipole component, deflects the incoming particles according to their charge, energy (rigidity), and angle of incidence. This defines a vertical cut-off rigidity P_c near the surface of the Earth below which the cosmic ray particles cannot reach according to

$$P_c = 14.9 \cos^4 \lambda_m,$$

where λ_m is the geomagnetic latitude and the constant 14.9 reflects the magnitude of the Earths dipole moment here taken to be 8.0×10^{25} EMU.

[5] With the above discussion as a very simplified background for the production of these nuclei in the atmosphere by cosmic rays, we note that the concentration of ^{10}Be in ice cores has now been measured in quite accurate temporal detail from ~1500 AD to the present time using ice core data from both Greenland and the South Pole [*Beer et al.*, 1990; *Beer et al.*, 1991; *Bard et al.*, 1997; *Steig et al.*, 1996]. The temporal variations of this isotope over this time period that have been measured, including both longer-term and shorter-term (11-year) solar variations, have recently been used to investigate the nature of the cosmic ray modulation process itself and the properties of the interstellar cosmic ray spectrum outside the heliosphere [*McCracken and McDonald*, 2001]. In the above studies, ^{10}Be is used in place of ^{14}C, which is generally measured in tree rings, because according to McCracken and McDonald, ^{10}Be appears to have less atmospheric mixing and a simpler phase lag of about 1 year.

[6] As a result of this new work by *McCracken and McDonald* [2001], studies of the ^{10}Be temporal variations now have the capability of essentially reversing the field of study of this cosmogenic nucleus, in the sense that the ^{10}Be temporal data may now be used to extend our knowledge of the cosmic ray modulation process and to investigate the properties of the local interstellar cosmic ray spectrum outside the heliosphere. To do this, however, requires improved calculations of the ^{10}Be production rate and other processes such as mixing which contribute to the ^{10}Be concentration changes. At the same time one must realize that most previous studies [e.g., *Beer et al.*, 1990; *Beer et al.*, 1991; *Steig et al.*, 1996] have assumed that atmospheric mixing between polar and equatorial latitudes is important. Such mixing could dilute the changes in ^{10}Be concentration to be expected from production alone.

[7] The data used in the work of *McCracken and McDonald* [2001] suggests that the total ^{10}Be concentration as measured in the Greenland ice core in the late 1600s near the time of the Maunder minimum in solar activity was a factor ~1.8–2.0 times higher than it was during the recent periods of minimum modulation in the solar 11-year cycle in 1965 and 1976. The recent ^{10}Be annual data from the same ice core suggest that the magnitude of the 11-year modulation in these two later cycles was also a factor of ~2, as measured by the changes in ^{10}Be concentration. We should note here that changes in the Earth's dipole moment and orientation over the last few hundred years are likely to account for changes of only ~5% in ^{10}Be production on the polar plateau [*McCracken*, 2001].

[8] Our present understanding of the solar modulation process describes this overall process as a "force field" modulation in the heliosphere [*Gleeson and Axford*, 1968]. Using recent cosmic ray data from neutron monitors and spacecraft, the modulation function ϕ in MV can be determined from these studies to be ~350–450 MV at sunspot minimum, increasing to ~1000–1200 MV at sunspot maximum. This changing modulation potential at the Earth may thus be responsible for the factor ~1.5–2.0 that is observed for the some of the recent 11-year changes in the ^{10}Be concentration from the Dye 3 ice core in Greenland [*Beer et al.*, 1994] as tabulated by *McCracken and McDonald* [2001]. The modulation potential of 350–450 MV associated with the sunspot minimum periods represents the overall solar modulation between the Earth and interstellar space at this time and is sometimes referred to as the residual modulation.

[9] To accurately calculate the ^{10}Be production that would be expected at high latitudes at sunspot minimum and sunspot maximum in the 11-year solar cycle and also for the lower modulation cases, extending to the case of zero modulation corresponding to the interstellar (IS) cosmic ray spectrum, we utilize an updated set of ^{10}Be production calculations starting with a new unmodulated (interstellar) cosmic ray spectrum. The recent work of *O'Brien et al.* [1991], *Masarik and Reedy* [1995], *Masarik and Beer* [1999], and *Reedy* [2000] provides a basis for these new production calculations. Developments in several areas make such a new calculation useful.

[10] First of all, the spectra of cosmic ray protons and helium nuclei have recently been determined with much greater precision at the Earth, which, along with our improved understanding of the solar modulation process as provided by the Voyager and Pioneer spacecraft in the heliosphere out to ~80 AU, allows more accurate interstellar cosmic ray spectra to be deduced [*Webber and Lockwood*, 2001]. Also, it is now possible to make improved calculations of the secondary production of protons and neutrons in the Earths atmosphere using advanced versions of Monte Carlo programs such as FLUKA [*Fasso et al.*, 2001a, 2001b]. This calculation of proton and neutron production may be checked against recent latitude surveys of nucleonic intensity using portable neutron monitors. New and improved cross section data also exist in many cases for the production of ^{10}Be and other cosmogenic isotopes from these atmospheric protons and neutrons [*Webber et al.*, 2003; *Nagai et al.*, 2000]. All of these factors make it worthwhile to reexamine the production of ^{10}Be in the atmosphere by cosmic rays.

[11] It is the goal of this paper to reexamine the atmosphere production of ^{10}Be using this new body of data and calculations. This production will then be compared with the temporal ^{10}Be production profiles described by *McCracken and McDonald* [2001]. Inferences and limits on the time variability of solar modulation and on the interstellar cosmic ray spectrum will then follow.

2. Calculation of the ^{10}Be Production Rate

2.1. General Approach

[12] The production rate, P_j, of ^{10}Be and other cosmogenic nuclides at a depth x in the atmosphere is described by

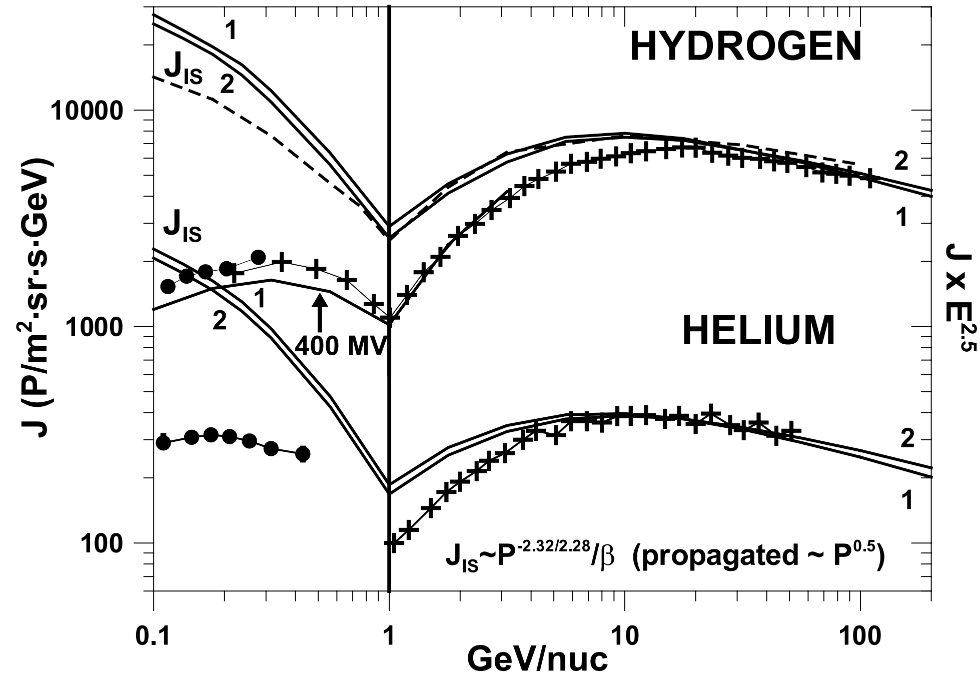

Figure 1. Calculated interstellar hydrogen and helium spectra according to *Webber and Lockwood* [2001]. Curve 1 is for an assumed source spectrum $\sim P^{-2.32}$. Curve 2 is for a source spectrum $\sim P^{-2.28}$. Plus symbols refer to data from the BESS magnetic spectrometer in 1997 [*Sanuki et al.*, 2000]; solid circles are IMP data in 1997 [*McDonald et al.*, 1998]. The difference between the interstellar spectra and the observed spectra is due to solar modulation, e.g., a curve giving the expected spectrum for a modulation potential of 400 MV is shown as a solid line. The interstellar hydrogen spectrum given by *Masarik and Beer* [1999] is shown as a dashed curve. The two spectra are normalized at 1 GeV. This normalization is necessitated by the fact that Masarik and Beer quote omnidirectional intensities and we use unidirectional ones. However, the relative shape of the two spectra showing a low energy excess in our spectrum will be maintained. (Note the scale on the RH axis is for dj/dE × $E^{2.5}$ spectra above 1 GeV/nuc, scale on LH axis is for direct dj/dE spectra below 1 GeV/nuc).

the equation

$$P_j(E,x) = \Sigma_i N_i \Sigma_k \int_0^\infty \sigma_{ijk}(E_k) \bullet J_k(E_k,x)dE \qquad (1)$$

where N_i is the number of atoms of the target element i per Kg of the atmosphere, σ_{ijk} is the cross section for the production of nuclide j from the target element i by particles of type k with energy E_k and J_k (E_k, x) is the total flux of particles of type k with energy E_k at depth x inside the atmosphere. J_k (E, x) is calculated starting with the primary cosmic ray spectrum as an input.

[13] In this paper we calculate the particle fluxes J_k (E_k, x) in the atmosphere using the 2002 version of the FLUKA code [*Fasso et al.*, 2001a, 2001b]. This is a Monte Carlo calculation that determines J_k (E_k, x) and then the production of the cosmogenic nuclides using production cross sections for these nuclides already included in the code. This code has the advantage of providing the J_k (E_k, x), e.g., energetic protons and neutrons, which may then be checked for accuracy using neutron monitor latitude surveys at several altitudes. Also the cosmogenic nuclide production is calculated as part of the same code.

2.2. Interstellar Cosmic Ray Input Spectra

[14] The calculation of particle production and transport in the atmosphere begins with the choice of the interstellar cosmic ray spectra. These spectra are only observed beyond ~100 AU. Inside this distance they are modulated according to the level of solar activity which includes 11-year and 22-year and longer cycles. In our calculations we use the interstellar proton and helium spectra derived from galactic cosmic ray propagation calculations by *Webber and Lockwood* [2001]. These interstellar spectra along with estimated errors are shown in Figure 1. Formulae to describe these spectra within ±10% between 0.1 and 100 GeV/nuc are given by

$$J_{IS}(E_p) = 21.1\left[E^{-2.80} \times \left(1 + 5.85\,E^{-1.22} + 1.18\,E^{-2.54}\right)^{-1}\right]$$
$$\text{particles/m}^{2}\cdot\text{sr}\cdot\text{s}\cdot\text{MeV/nuc} \qquad (2a)$$

$$J_{IS}(E_{He}) = 1.075\left[E^{-2.80} \times \left(1 + 3.91\,E^{-1.09} + 0.90\,E^{-2.54}\right)^{-1}\right]$$
$$\text{particles/m}^{2}\cdot\text{sr}\cdot\text{s}\cdot\text{MeV/nuc} \qquad (2b)$$

where E is in GeV/nuc. The accuracy of these spectra is estimated to be ~±10% above 1 GeV/nuc, but the spectra become less certain at lower energies, particularly below ~0.1 GeV/nuc.

[15] These spectra have been used as inputs to the solar modulation calculations that successfully predict the intensities of various energy protons and helium nuclei observed

Table 1. $Z \geq 2$ Nuclei Contribution at 10 GeV/nuc

Species	Relative Intensity, J (at 10 GeV/nuc)	Nucleons	J × N
He	13.0	×4	=52
Z = 5–8	1.1	×14	=15.5
Z = 9–14	0.24	×25	=6.0
Z = 16–20	0.025	×38	=1.0
Z = 21–25	0.023	×50	=1.2
Fe	0.046	×56	=2.6
			Σ = 78.3
			=1.51 × N(He)

by spacecraft near the Earth and by the Voyager and Pioneer spacecraft in the heliosphere out to ~80 AU [*Webber and Lockwood*, 2001].

[16] For the contribution of nuclei with Z > 2 we use the abundances determined above several GeV/nuc by *Webber* [1997] for various charge groups as listed in Table 1. These abundances result in a total contribution of He and heavier nuclei = 1.51 times the He contribution at a fixed energy/nucleon.

[17] For the relative contribution of protons and $Z \geq 2$ nuclei to the production of the cosmogenic nuclei in the Earths atmosphere we note that at a fixed location on Earth the geomagnetic cut-off is a function of rigidity. So the relative contribution of protons and heavier nuclei must be expressed in rigidity whereas the spectral measurements are frequently determined as a function of energy or energy/nuc. At a sufficiently high rigidity where the modulation is small, e.g., 20 GV, the intensity ratio of protons to He nuclei from Figure 1 is ~5.5 ± 0.2. Thus at a fixed rigidity the number of nucleons from all $Z \geq 2$ nuclei is 4.0 × 1.51/5.5 = 1.10 times the number from protons. However these nucleons are approximately a factor of 2 lower energy/nucleon.

[18] Using the specific yield curves versus rigidity (e.g., Figure 5 for ^{10}Be) (or energy/nuc for protons), we find these curves scale as (rigidity)$^{0.13}$ above 5 GV. Thus at a given energy the production from individual nucleons for $Z \geq 2$ relative to protons will scale as $1/(2.0)^{0.13} = 0.91$, and the overall contribution from $Z \geq 2$ nuclei will be ~1.10 × 0.91 = 1.0 or approximately the same as for protons. Thus the yield curves for protons are multiplied by (1.0 + 1.0 = 2.0) to account for $Z \geq 2$ nuclei. This simple factor is used to scale the proton production for $Z \geq 2$ nuclei above ~10 GV. At lower rigidities this factor is evaluated numerically to provide the correct multiplication factor which eventually goes to ~1.0 (protons only) at rigidities below a few GV, where the yield from $Z \geq 2$ nuclei rapidly goes to zero because of their lower energy at a fixed rigidity.

2.3. Solar Modulation Calculations

[19] The solar modulation in the heliosphere is described in these calculations to be a force field equation of the form originally described by *Gleeson and Axford* [1968]:

$$J_e(E,\Phi) = J_{IS}(E+\Phi)\left(E^2 + 2m_pc^2 E\right) \Big/ \left[(E+\Phi)^2 + 2\,m_pc^2(E+\Phi)\right] \tag{3}$$

where J_e is the spectrum measured at the Earth, J_{IS} is the interstellar spectrum at energy E + Φ, Φ is the modulation

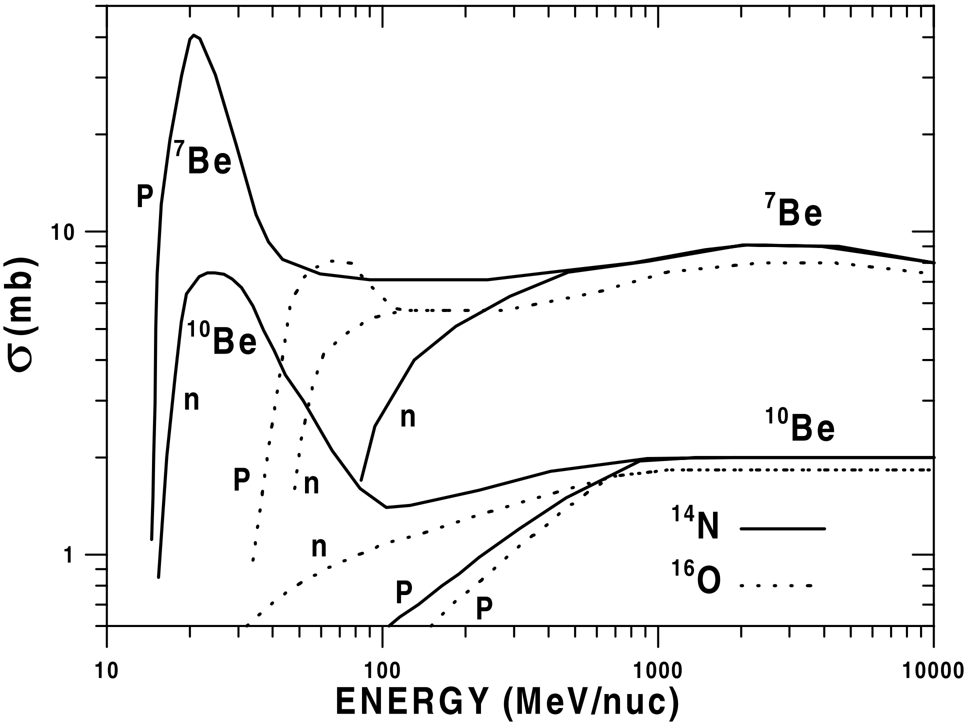

Figure 2. Cross sections for production of ^{7}Be and ^{10}Be from proton and neutron interactions with ^{14}N and ^{16}O. Solid and dashed lines above ~100 MeV/nuc are from the new cross sections formulation in the work of *Webber et al.* [2003] based on higher energy data. Solid and dashed lines below ~100 MeV/nuc are from lower energy data as described in the text.

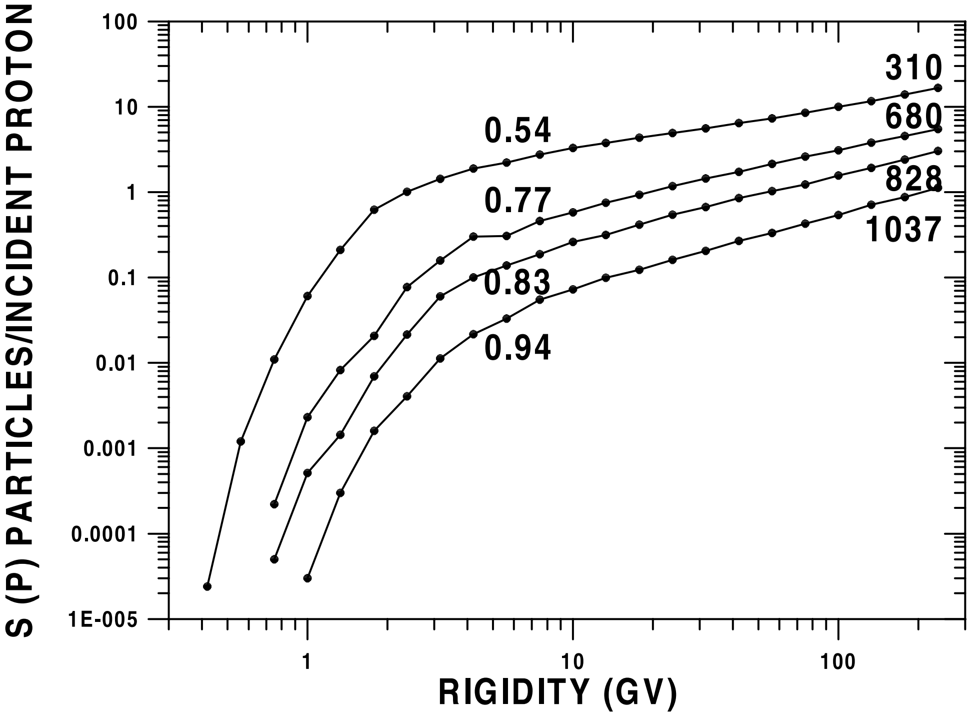

Figure 3. Calculated specific yields for the production of nucleons as a function of rigidity for various depths in the atmosphere as obtained from the FLUKA program. Numbers next to curves give the altitude in g/cm^2 and the power law dependence of S(P) $\sim P^{-x}$ above ~5 GV.

potential in MV, m_pc^2 is the proton rest mass energy. This representation, which is equivalent to a heliospheric potential Φ, which produces an energy loss, is found to reproduce the measured solar modulation effects seen on cosmic rays at the Earth and by the Voyager and Pioneer spacecraft to a high level of accuracy.

2.4. Nuclear Cross Sections for ^{10}Be (and ^{7}Be) Production

[20] The available cross sections for production of ^{10}Be (and ^{7}Be) in the atmosphere from interactions with ^{14}N and ^{16}O are shown in Figure 2. These are obtained from a new parametric cross-section program [*Webber et al.*, 2003], which is designed to give a best fit to all of the available measurements above ~150 MeV/nuc, along with various individual measurements at lower energies [*Schiekel et al.*, 1997; *Sisterson et al.*, 1997; *Nagai et al.*, 2000]. Note that these cross sections behave in a fairly orderly way as a function of energy, except for two prominent exceptions below ~100 MeV/nuc. For proton interactions with ^{14}N there is a resonance for ^{7}Be production peaking at ~20–25 MeV/nuc. Since the proton fluxes in the atmosphere are greatly suppressed due to ionization energy loss, this resonance contributes only a few percent to the total ^{7}Be production. For neutron interactions with ^{14}N there is also a resonance for ^{10}Be production peaking at ~20–30 MeV/nuc. In this case, because of the much higher neutron flux in the atmosphere at these energies, this resonance contributes ~50% of all ^{10}Be production in the atmosphere and could be an important source of ^{10}Be from solar cosmic rays as well.

[21] In the calculations we have used the production cross sections for ^{7}Be and ^{10}Be currently in the FLUKA program. For ^{10}Be these cross sections agree within ±10% with those given in the *Webber et al.* [2003] program above 100 MeV and with the solid curves in Figure 2 below 100 MeV/nuc. However, for ^{7}Be the values for production from ^{14}N lie 30–35% below those indicated by the solid curves in Figure 2, whereas those for ^{7}Be production from ^{16}O are ~60% below those indicated by the dashed curves for this reaction (e.g., the *Webber et al.* [2003] cross sections). We have therefore multiplied the total ^{7}Be specific yield from the FLUKA program by a factor of 1.45 to account for these differences. This makes the ^{7}Be production specific yield curve in Figure 5 on average ~1.8 times that for ^{10}Be, so the production of ^{7}Be should be ~1.8 times that for ^{10}Be. This agrees better with the recent calculations of *Nagai et al.* [2000] and also with direct measurements of the temporal variations of the ^{7}Be/^{10}Be ratio which place this ratio in the range 1.3–1.9. Note that these corrections for ^{7}Be do not in any way affect our calculations for ^{10}Be.

3. Results and Discussion

3.1. Nucleon Production in the Atmosphere and a Comparison With Measurements

[22] In Figure 3 we show the relative specific yield of all nucleons >1 MeV at various depths in the atmosphere calculated as a function of incident nucleon (proton) rigidity using the FLUKA program. At each logarithmically spaced rigidity interval (8 to the decade)10^5 protons are incident on the top of the atmosphere in this Monte Carlo calculation. This calculation includes the contribution of $Z \geq 2$ nuclei as described above. A calculation of nucleon specific yields at sea level using an earlier version of the FLUKA program gives very similar results [*Clem and Dorman*, 2000]. These

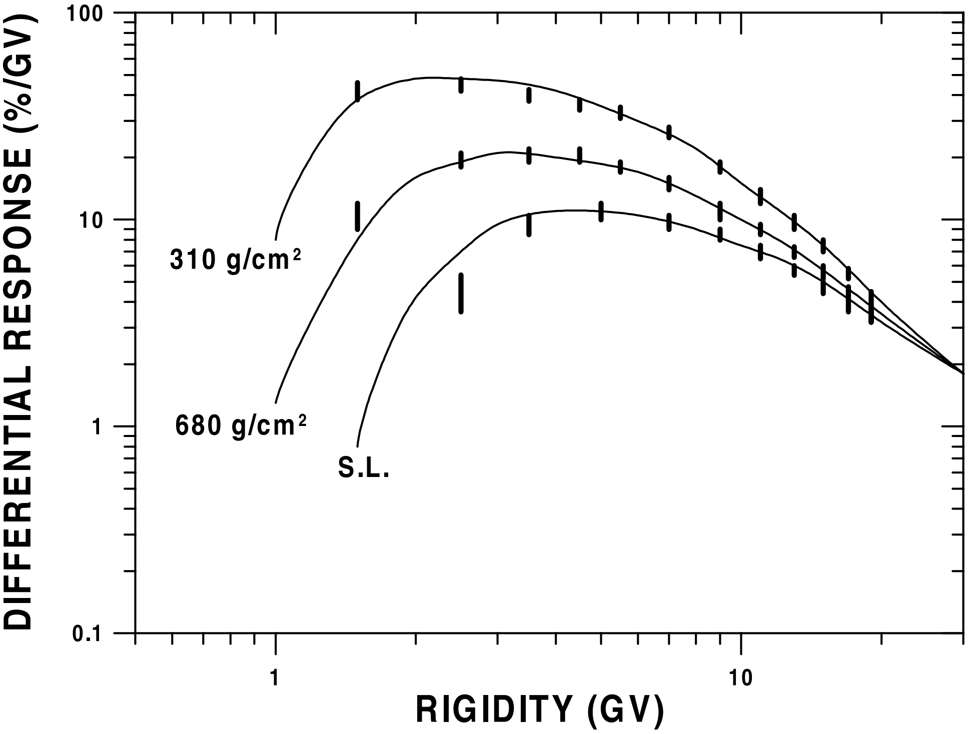

Figure 4. The calculated differential response curves for nucleons in the atmosphere at various depths, compared with measurements (solid error bars) using portable neutron monitors [*Stoker*, 1994; *Bieber et al.*, 1997].

specific yields may be used to calculate the expected nucleon production in the atmosphere as a function of rigidity (geomagnetic latitude) and atmospheric depth for comparison with direct measurements using the relationship where J_i (P) are the cosmic ray rigidity spectra

$$dN(P,x) = \Sigma \int_{Pc}^{\infty} S_i(P,x)J_i(P)dP \qquad (4)$$

incident on the Earths atmosphere ($\equiv J_e$ (E, Φ)) and S_i (P, x) is the specific yield function for protons shown in Figure 3 as derived from the FLUKA program. The sum over i represents the contribution of all $Z \geq 2$ nuclei and dN (P, x) represents the measured differential response curves as derived from the measured neutron monitor latitude curves [*Stoker*, 1994; *Bieber et al.*, 1997].

[23] The calculated differential response curves for atmospheric nucleon production at three atmospheric depths are shown in Figure 4, along with latitude responses measured by portable neutron monitors carried on aircraft and on ships [*Stoker*, 1994; *Bieber et al.*, 1997]. The excellent agreement between the predictions and the measurements for both the latitude and depth dependence of atmospheric nucleon production suggests that the FLUKA program is indeed providing accurate calculations of the production of nucleons in the atmosphere.

[24] The calculated total atmospheric specific yields, S(P), of ^{7}Be and ^{10}Be are obtained by injecting 10^5 protons at each logarithmically spaced rigidity (8 to the decade) between 0.316 to 316 GV vertically at the top of the atmosphere and are shown in Figure 5. This rigidity range is chosen to completely cover the range of sensitivity for Be production from galactic cosmic rays. This calculation represents the atmospheric part of the production calculation described by equation (1). If these yields are then multiplied by the appropriately modulated primary spectrum (equations (2a) and (2b)), including the effects of $Z \geq 2$ nuclei, we obtain the production rates of ^{10}Be as a function of rigidity and solar modulation level as shown in Figure 6. These production rates exhibit a maximum at ~2 GV, which increases to ~3 GV for larger modulation levels. The production below ~0.5 GV is a small fraction of the production at the peak at all modulation levels for the typical interstellar cosmic ray spectrum used here. In terms of a geomagnetic cut-off latitude, 2 GV corresponds to ~52° and 0.5 GV to ~63° for normal vertical cut-offs. So for all solar modulation levels there exists what amounts to a polar plateau at ~63°, above which the ^{10}Be production remains essentially constant for a fixed level of solar modulation. Note the ^{10}Be production is much more sensitive to lower rigidity cosmic rays than the neutron monitor response curves near sea level shown in Figure 4.

[25] In Figure 7 we show this ^{10}Be production as a function of geomagnetic latitude for different solar modulation levels as obtained by assuming normal vertical cut-offs at each latitude. In this figure the polar plateau above ~63° is clearly evident. The geomagnetic latitudes of this polar plateau include the ice core measurements sites for the ^{10}Be data in Greenland and the South Pole. Therefore, unless there is a significant latitudinal mixing of ^{10}Be production, for which *McCracken and McDonald* [2001] argue is not the case, but for which there is considerable debate, [e.g., *Beer et al.*, 1990; *Steig et al.*, 1996] the

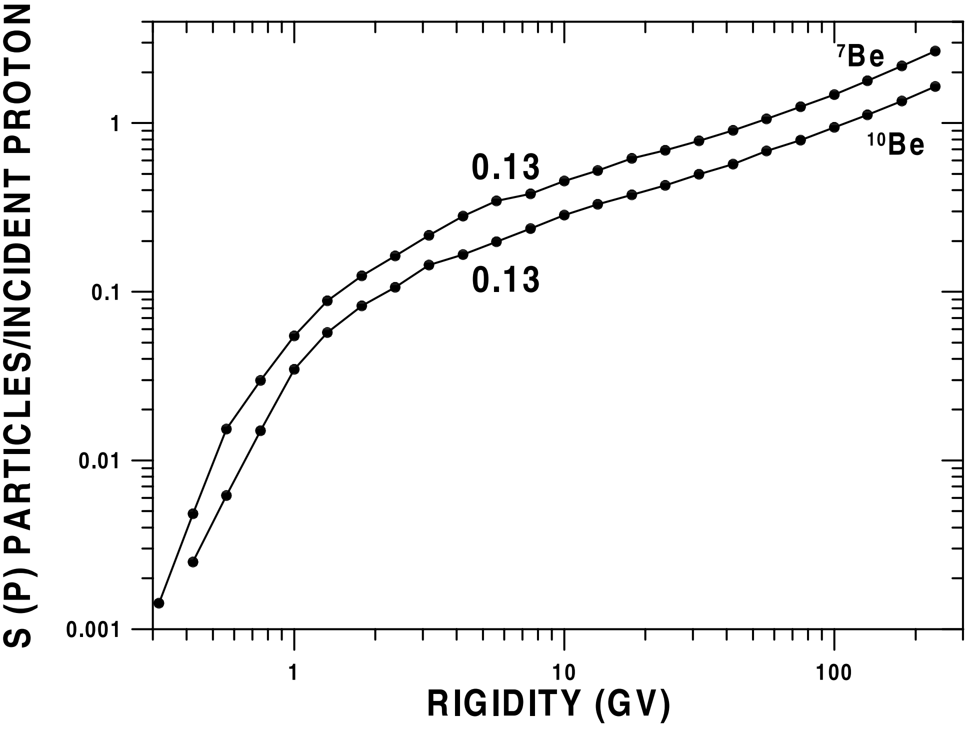

Figure 5. Calculated specific yields for the total production of ^{7}Be and ^{10}Be nuclei in the atmosphere as a function of rigidity using the FLUKA program. Yields for ^{7}Be shown in this figure have been multiplied by the factor 1.45 as described in the text to account for differences in the FLUKA cross sections are those presented in Figure 2. These yields for ^{7}Be are ~1.8 times those for ^{10}Be. Numbers next to curves give the power law dependence of S(P) ~ P^{-x} above 5 GV.

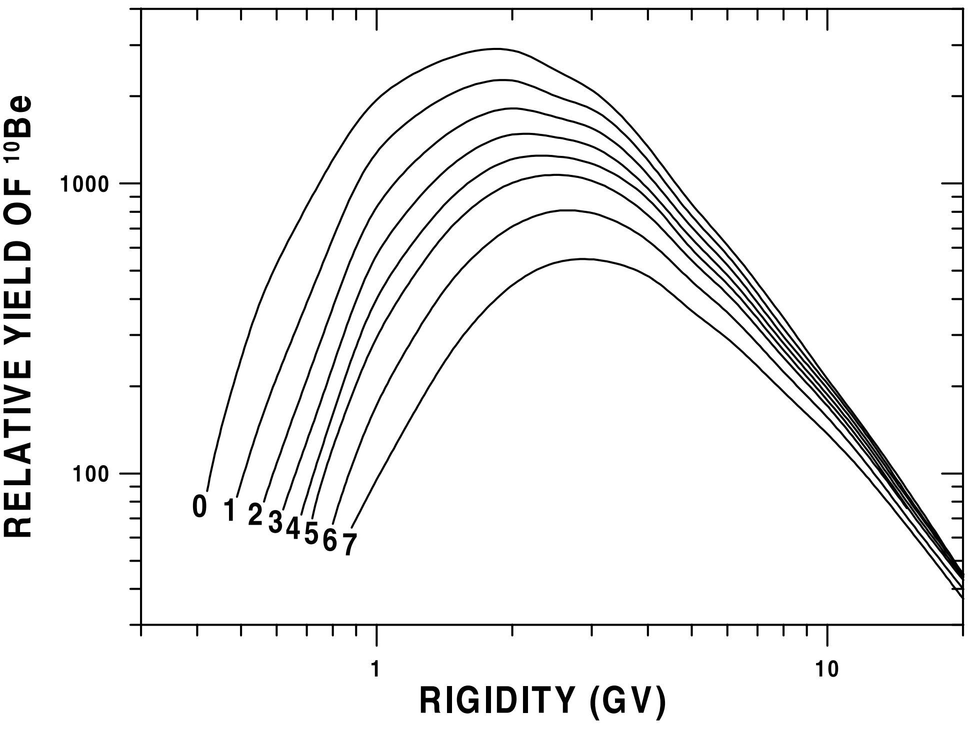

Figure 6. The production rates of ^{10}Be (in arbitrary units) in the atmosphere as a function of rigidity and solar modulation level. These curves are obtained from those in Figure 5 by multiplying by the primary spectrum times the solar modulation level as given by equation (3). Curve O = 0 MV solar modulation level, 1 ≡ 100 MV, 2 ≡ 200 MV, 3 ≡ 300 MV, 4 ≡ 400 MV, 5 ≡ 500 MV, 6 ≡ 700 MV, 7 ≡ 1000 MV.

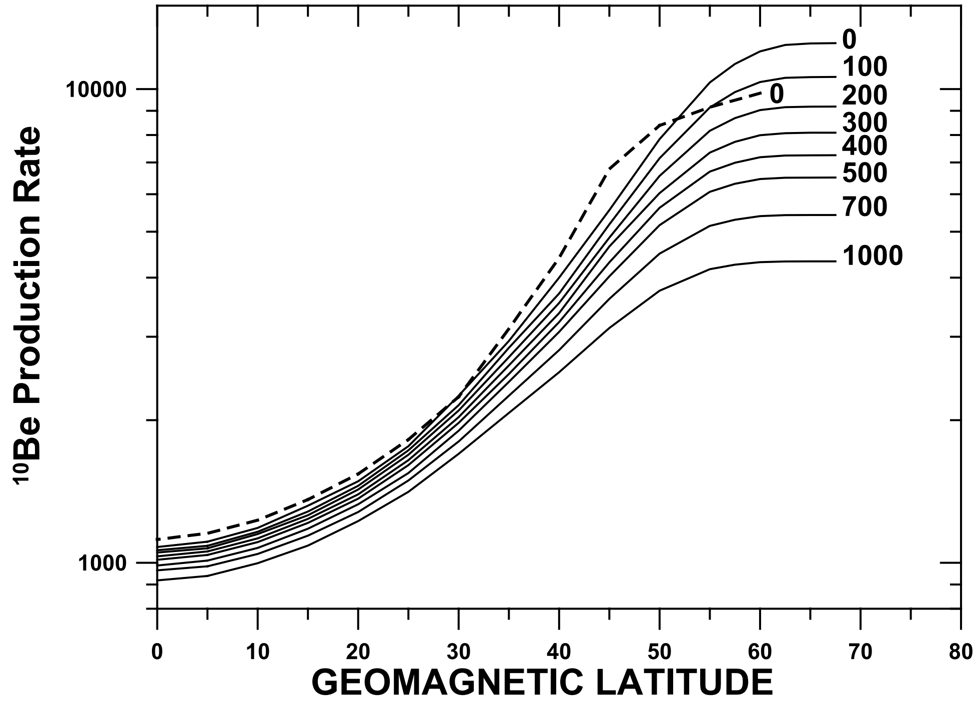

Figure 7. Total ^{10}Be production (in arbitrary units) in the atmosphere as a function of geomagnetic latitude and solar modulation level. The total ^{10}Be production from *Masarik and Beer* [1999] for a solar modulation ϕ = 0 normalized at a latitude of 30° is shown for illustration as a dashed line.

changes in production rates of ^{10}Be on this polar plateau should accurately track changes due to solar modulation. Note that the fraction of ^{10}Be production occuring at high latitudes is somewhat higher in this latest calculation than some previous calculations as illustrated by the dashed line in Figure 7 from *Masarik and Beer* [1999] for ϕ = 0 MV modulation. This difference has implications for latitudinal mixing of ^{10}Be since now somewhat more of the ^{10}Be production is at the higher latitudes.

[26] In Table 2 we show the calculated production rates on the polar plateau as a function of solar modulation level, normalized to 100 for zero modulation (corresponding to the interstellar spectrum). Note that for the 11-year maximum to minimum modulation (if we assume that the maximum and minimum correspond to typical solar modulation levels of 400 and 1200 MV) the total change in ^{10}Be production is a factor of 1.89. The change in the ^{10}Be production between the minimum 11-year modulation levels, assumed to correspond to ~400 MV, and the interstellar spectrum itself corresponds to a factor of 1.72. Recall that earlier we noted that the 11-year variation in the recent ^{10}Be concentration in the Greenland ice core data is observed to be a factor ~1.5–2.0 and the increase in ^{10}Be concentration from the recent solar minima in 1965 and 1976 to the Maunder minimum time period in the late 1600s appears to be a factor ~1.8–2.0.

4. Comparison of Historical ^{10}Be Records, Direct Cosmic Ray Records, and Predictions of Solar Modulation Models

[27] Simultaneous ^{10}Be records and direct cosmic ray records exist for the solar cycles with minima in 1954, 1965, and 1977. Continuous neutron monitor data begins in about 1953. Continuous spacecraft data can be extended back to about 1963. High-altitude, balloon-borne ion chamber data extends in one case back to 1933 and more detailed temporal data using this technique covers the time period from about 1950 to 1970 [*Neher et al.*, 1953; *Neher*, 1967]. A summary of all of this cosmic ray data, along with recent available ^{10}Be data from Greenland is shown in Figure 8. All of the data is normalized to 100 for the average at the minima in 1965 and 1976. This figure shows that the magnitudes of the 11-year temporal variations of ^{10}Be concentration, the spacecraft data for cosmic rays >70 MeV and the high-altitude ion chamber data are very similar. These temporal variations during an 11-year solar cycle are typically a factor ~2.0. The neutron monitor data, because of the higher average energy of

Table 2. ^{10}Be Production on the Polar Plateau (λ_{gm} > 63°) as a Function of Solar Modulation Level

Solar Modulation	Total Production (Arbitrary Units)	Relative Production	Ratios[a]
0 MV	12,500	100	——
100 MV	10,610	84.9	↑
200 MV	9185	73.5	1.72 x
300 MV	8090	64.7	↓
400 MV	7250	58.0	——
500 MV	6505	52.0	↑
700 MV	5422	43.4	1.89 x
1000 MV	4328	34.6	↓
1200 MV	3850	30.7	——

[a] The production ratios for 400 MV to 1200 MV and 0 MV to 400 MV are 1.89 and 1.72, respectively. Comparisons of these predicted ratios with recent ^{10}Be measurements of the 11-year solar cycle and the Maunder minimum measurements are discussed in the text.

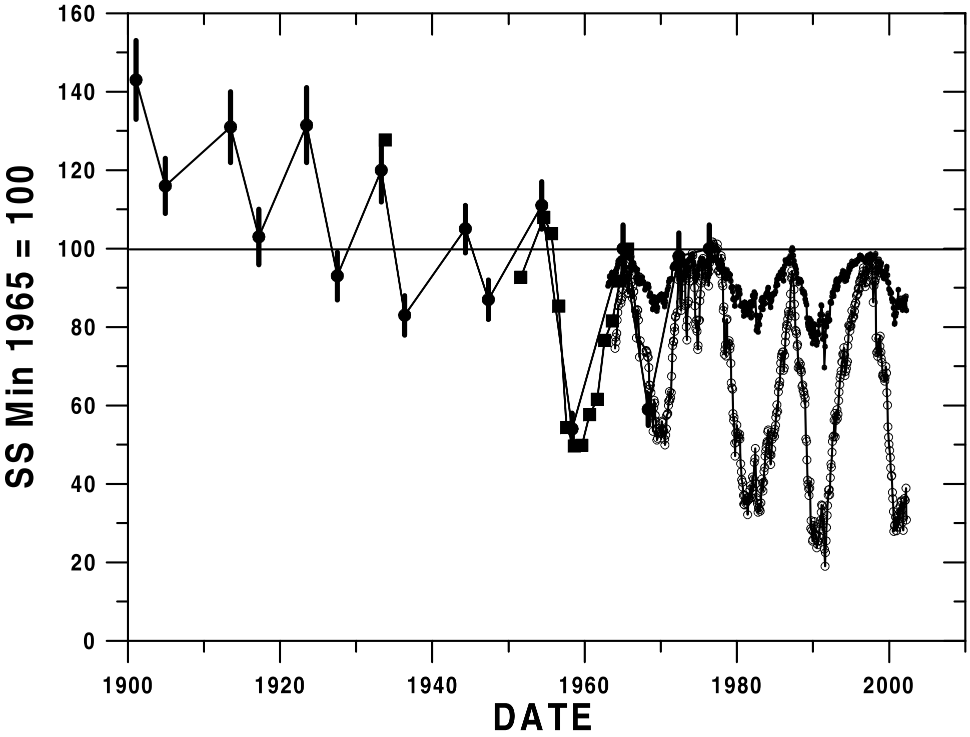

Figure 8. Temporal variations of cosmic rays and ^{10}Be observed from 1933 to the present. All variations are normalized to 100 for the average of the solar minima in 1965 and 1976. The cosmic ray data shown include (1) high-latitude Mt. Wash plus Climax neutron monitor (solid circles); (2) integral >70 MeV cosmic ray rates from spacecraft [*Lockwood et al.*, 2001] (open circles); (3) high-altitude balloon data from ionization chambers [*McCracken and McDonald*, 2001; *Neher*, 1967] (solid squares); (4) ^{10}Be concentrations at minima and maxima of the solar cycle [*McCracken and McDonald*, 2001] (large solid circles with error bars).

response, shows much smaller temporal variations (~20% for an 11-year cycle) and therefore is not as useful for comparison purposes.

[28] The times of minimum 11-year modulation, the so-called residual modulation between the Earth and the IS cosmic ray spectrum, are of particular interest. For the minima in 1965, 1976, 1987, and 1997 the cosmic ray intensities, as determined from the spacecraft and neutron monitor data, are identical within ±5%. There is evidence of a 22-year intensity wave of amplitude ~±3% with maxima in 1976 and 1997 [*Webber and Lockwood*, 1988]. The high-altitude ion chamber data covers the solar cycle from 1954 to 1965 particularly well. The total ionization rate at 15 g/cm^2 atmospheric depth in 1954 is higher than in 1965 by 12 ± 2% according to *Neher* [1967]. This could be the result of an exaggerated 22-year wave which would be expected to be at a maximum in 1954 on the basis of the spacecraft data just discussed or it could be part of a longer-term trend. It should be noted that the sunspot number at the 1954 minimum was lower, and this low period lasted for a longer time in the 1954 minimum than in subsequent sunspot minima. In 1965 the lowest yearly average sunspot number was 10.2, whereas in 1954 it was only 4.4 with several months of values <1.0, values never seen in subsequent sunspot minima through 1997.

[29] Extending ion chamber data back to earlier times when the measurements began in 1933 is more difficult. However, on the basis of careful comparisons based on data from ionization chamber studies by *Neher et al.* [1953] and *Neher* [1967], *McCracken and McDonald* [2001] concluded that the 1933 high-altitude ion chamber data corresponded to a rate ~15% higher than that observed in 1954. Thus including the change between 1954 and 1965, the total increase in the high altitude ion chamber data between 1965 and 1933 is ~ 25–30%.

[30] This increase over time is also observed in the ^{10}Be concentration data from the Dye 3 ice core [*Beer et al.*, 1994]. Again using this data as shown by *McCracken and McDonald* [2001], the ^{10}Be concentration in 1954 appears to be ~10% higher than in 1965 and the ^{10}Be concentration in 1933 is also higher than in 1965. This is part of a longer term increase in ^{10}Be concentration at times of sunspot minimum that reaches a maximum concentration in 1902 that is ~45% higher than that observed in 1965 (see Figure 2 of McCracken and McDonald). The errors on the individual ^{10}Be data points due to counting statistics only are estimated to be ±7%. This increase between 1965 and 1902 is a large fraction of the total increase in ^{10}Be concentration of 1.8–2.0 times between 1965 and the Maunder minimum seen in the Dye ice core data.

[31] We therefore believe that both the high-altitude ion chamber data and the ^{10}Be concentration data (1) correlate well with each other and generally support the temporal variations seen by each other over several sunspot minima

and (2) support the argument that the cosmic ray intensity at times of sunspot minimum has increased significantly in the past, corresponding to a decrease in the amount of residual solar modulation. If we assume that this residual modulation in 1965 corresponded to a modulation potential of 400 MV, then according to the calculations in Table 2, in 1954 the modulation potential was 300 MV, in 1933 it was 220 MV, in 1902 it was 100 MV, and in 1695 the ^{10}Be concentration would actually be slightly higher than that predicted for zero modulation (IS spectrum). A choice of the modulation potential in 1965 of 480 MV instead of 400 MV would make the calculated ^{10}Be concentration at zero modulation equal to that observed in 1695. Errors of ±50 MV in the value of the modulation potential assigned to the 1965 minimum as well as overall errors of possibly ±10% in the relative ^{10}Be concentration values for 1695 and 1965 mean that the ^{10}Be data are consistent with essentially no solar modulation at the time at the end of the Maunder minimum in 1695, based on the interstellar proton spectrum used in this paper. Or to put it another way, the interstellar spectrum estimated by *Webber and Lockwood* [2001] provides a consistent interpretation of the historical ^{10}Be concentration data in terms of essentially zero solar modulation in 1695, assuming that latitudinal mixing effects are relatively unimportant on both the long-term and short-term scale.

5. Summary and Conclusions

[32] We have examined the production of ^{10}Be by cosmic rays in the Earth's atmosphere. This new study uses the most recent estimates of the interstellar cosmic ray spectrum and the effects of solar modulation as obtained from cosmic ray measurements on the IMP spacecraft at the Earth and on the Voyager and Pioneer spacecraft in the outer heliosphere. The latest version of the FLUKA Monte Carlo code is used to calculate the production of nucleons in the Earths atmosphere and from these nucleons to calculate the ^{10}Be (^{7}Be) production. This production is presented as a function of geomagnetic latitude and solar modulation level. The specific yield of these cosmogenic isotopes is found to be a very sensitive indicator of the low rigidity part of the cosmic ray spectrum with a maximum sensitivity at ~2 GV.

[33] The motivation for these studies comes from the work of *McCracken* [2001] and *McCracken and McDonald* [2001], who argued that ^{10}Be observed in ice cores on the polar plateau probably originated at high latitudes and precipitated to Earth in about 1 year. Also, ^{10}Be production rates on the polar plateau are little affected by geomagnetic field changes in the last few hundred years. Thus these ice core records of ^{10}Be concentration extending back several hundred years can be used to study the amount of solar modulation of cosmic rays on this time scale.

[34] These ice core records from Greenland indicate that the ^{10}Be concentration at the time of the Maunder minimum in the late 1600s was ~1.8–2.0 times what it was during the recent sunspot minima in 1965 and 1976. These records also indicate that the ^{10}Be concentration during recent 11-year solar cycles varied by a factor ~1.5–2.0. Our ^{10}Be production calculations show that during a typical 11-year solar modulation cycle, when the modulation potential varies from ~400 to 1200 MV as is required to explain the temporal variations observed by spacecraft, the ^{10}Be production on the polar plateau will vary by a factor ~1.9 times in agreement with the concentration changes observed in ice core data. The ice core data also shows a systematic increase in ^{10}Be concentration at the times of minimum solar modulation in the 11-year cycle starting in 1954 and extending back to the minimum in 1902 when the ^{10}Be concentration was ~1.45 times that at the sunspot minima in 1965 and 1976. This increase is confirmed by early ion chamber measurements of total cosmic ray intensity at high altitudes for the 1933, 1954, and 1965 sunspot minima by *Neher et al.* [1953] and *Neher* [1967]. Using the estimated interstellar H and He cosmic ray spectra from the Voyager spacecraft and other data, these increased ^{10}Be concentration rates and the higher cosmic ray ion chamber rates would correspond to modulation potentials of 300, 220, and 100 MV in 1954, 1933, and 1902, respectively, provided these concentration changes are due to production changes only. These decreasing modulation potentials for solar minimum (the so-called residual modulation between the Earth and interstellar space) are one of the principal new conclusions of this paper.

[35] The even higher ^{10}Be concentration observed at the Maunder minimum in the late 1600s (~30% higher than in 1902) can be explained by the almost complete absence of solar modulation resulting in much higher ^{10}Be production. In other words, nearly the full IS cosmic ray spectrum (above ~1 GV rigidity) could have been incident on the Earth in the inner heliosphere at least at certain times during the Maunder minimum. This variation of the residual solar modulation at the minima in the 11-year cycle that is implied by the ^{10}Be temporal variations in this scenario must be related to changing conditions between the Earth and the outer regions of the heliosphere perhaps extending to beyond ~100 AU. Current solar modulation theories based on observations from the last 50 years or so that include a highly supersonic solar wind which ultimately leads to a termination shock at the pressure balance point between this wind and the interstellar medium pressure, beyond which a large fraction of the solar modulation appears to occur, need to be reexamined to successfully explain how such low modulation levels could be achieved.

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References

Bard, E., et al., Solar modulation of cosmogenic nuclide production over the last millennium: Comparison between ^{14}C and ^{10}Be records, *Earth Planet Sci. Lett.*, *150*, 453–462, 1997.

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

Beer, J., G. M. Raisbeck, and F. Yiou, Time variations of ^{10}Be and solar activity, in *The Sun in Time*, pp. 343–359, Univ. of Ariz. Press, Tucson, Ariz., 1991.

Beer, J., et al., Solar variability traced by cosmogenic isotopes, in *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, pp. 291–300, Cambridge Univ. Press, New York, 1994.

Bieber, J., P. Evenson, J. E. Humble, and M. I. Duldrig, Cosmic ray spectra deduced from neutron monitor surveys, *Proc. Int. Conf. Cosmic Rays 25th*, 45–49, 1997.

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

Fasso, A., et al., Electron-photon transport in FLUKA: Status, in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation, and Applications: Proceedings of the Monte Carlo 2000 Conference, Lisbon,* *23–26 October 2000*, edited by J. C. Barao et al., pp. 955–960, Springer-Verlag, New York, 2001a.

Fasso, A., et al., FLUKA: Status and prospective for hadronic applications, in *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation, and Applications: Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23–26 October 2000*, edited by J. C. Barao et al., pp. 159–164, Springer-Verlag, New York, 2001b.

Gleeson, L. J., and W. I. Axford, Solar modulation of galactic cosmic rays, *Astrophys. J.*, *154*, 1011–1018, 1968.

Lockwood, J. A., W. R. Webber, and H. J. Debrunner, Differences in the maximum intensities and the intensity-time profiles of cosmic rays in alternate solar magnetic field polarities, *J. Geophys. Res.*, *106*, 10,635–10,644, 2001.

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

Masarik, J., and R. C. Reedy, Terrestrial cosmogenic-nuclide production systematics calculated from numerical simulations, *Earth Planet. Sci. Lett.*, *136*, 381–395, 1995.

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 Rays 27th*, 44–47, 2001.

McCracken, K. G., and F. B. McDonald, The long-term modulation of the galactic cosmic radiation, 1500–2000, *Proc. Int. Conf. Cosmic Rays 27th*, 40–43, 2001.

McDonald, F. B., N. Lal, and R. E. McGuire, Cosmic ray recovery and the solar minimum phase of solar cycle 22: An interim report, *J. Geophys. Res.*, *103*, 373, 1998.

Nagai, H., W. Tada, and T. Kobayashi, Production rates of ^{7}Be and ^{10}Be in the atmosphere, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *172*, 796–801, 2000.

Neher, H. V., Cosmic-ray particles that changed from 1954 to 1958 to 1965, *J. Geophys. Res.*, *72*, 1527–1539, 1967.

Neher, H. V., V. Z. Peterson, and E. A. Stern, Fluctuations and latitude effect of cosmic rays at high altitudes and latitudes, *Phys. Rev.*, *90*, 655–674, 1953.

O'Brien, K., A. 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*, pp. 317–342, Univ. of Ariz. Press, Tucson, Ariz., 1991.

Reedy, D. C., Predicting the production rates of cosmogenic nuclides, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *172*, 782–785, 2000.

Sanuki, T., et al., Precise measurement of the cosmic ray proton and helium spectra with the BESS spectrometer, *Astrophys. J.*, *545*, 1135, 2000.

Schiekel, T., et al., Nuclide production by proton-induced reactions on elements Z ($6 \leq Z \leq 29$) in the energy range from 200 MeV to 400 MeV, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *114*, 91–119, 1997.

Sisterson, J. M., et al., Measurement of proton production cross section of ^{10}Be and ^{26}Al from elements found in lunar rocks, *Nucl. Instrum. Methods Phys. Res., Sect. B*, *123*, 324–329, 1997.

Steig, E. J., P. J. Polissar, M. Stuiver, P. M. Grootes, and R. C. Finkel, Large amplitude solar modulation cycles of ^{10}Be in Antarctica: Implications for atmospheric mixing processes and interpretation of the ice core record, *Geophys. Res. Lett.*, *23*, 523–526, 1996.

Stoker, P. H., Neutron monitor latitude surveys, response functions and 22-year modulation, *Proc. Int. Conf. Cosmic Rays 24th*, 1082–1085, 1994.

Webber, W. R., New experimental data and what it tells us about the sources and acceleration of cosmic rays, *Space Sci. Rev.*, *81*, 107–142, 1997.

Webber, W. R., and J. A. Lockwood, Characteristics of the 22-year modulation of cosmic rays as seen by neutron monitors, *J. Geophys. Res.*, *93*, 8735, 1988.

Webber, W. R., and J. A. Lockwood, Voyager and Pioneer spacecraft measurements of cosmic ray intensities in the outer heliosphere: Toward a new paradigm for understanding the global solar modulation process: 1. Minimum solar modulation (1987 and 1997), *J. Geophys. Res.*, *106*, 29,323–29,331, 2001.

Webber, W. R., et al., Updated formula for calculating partial cross sections for nuclear reactions of nuclei with $Z \leq 28$ and $E > 150$ MeV nucleon-1 in hydrogen targets, *Astrophys. J. Suppl.*, *144*, 153–167, 2003.

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