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Variations in the cosmic radiation, 1890–1986, and the solar and terrestrial implications

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Abstract

Comparison of cosmogenic ^{10}Be data and the records from several independent cosmic ray instruments for the period 1933–1977 demonstrates that the ^{10}Be data provide a reliable measure of the ~2 GeV/nucleon cosmic ray intensity at Earth, over short (~5 years) and long (>20 years) time scales. The ^{10}Be data show that the cosmic ray flux at sunspot minimum was anticorrelated with Z_{min}, the sunspot number at solar minimum over the interval 1901–1986. There was a 26% enhancement in the ^{10}Be data in the interval 1951–1954, and the data from two independent cosmic ray instruments verify that this was due an influx of low energy (<3 GeV/nucleon) cosmic radiation. It is suggested that this enhancement was associated with the very low sunspot number in 1954 (one of the lowest outside the Maunder and Dalton Minima), and with an anomalous cosmic ray diurnal variation in 1954. It is proposed that these several observations are the consequence of cosmic ray drift effects, and that the heliomagnetic field was relatively ordered in 1954. It is shown that the enhancement of 1954 is not consistent with the several models of the open solar magnetic field, unless factors other than the magnetic field strength are taken into account. Using the instrumental and ^{10}Be data, the cosmic ray spectra are estimated for 1965, 1954, 1890–1895, 1810–1820, and 1680–1720. From these, the ionization in the Earth's polar atmosphere is estimated for each of these periods.

Keywords: Cosmic radiation modulation; ^{10}Be measurements; Interplanetary magnetic field; Solar-terrestrial physics; Polar ionization

1. Introduction

It is well recognized that the concentration of ^{10}Be nuclei in polar ice exhibits temporal variations in response to changes in the flux of the primary cosmic radiation (Beer et al., 1991; Masarik and Beer, 1999, and references therein). McCracken (2001, 2004) has shown that the ^{10}Be response function has peaked near 1.8 GeV/nucleon since 1950, the peak being at lower energies at times of less intense modulation (e.g., it was 0.8 GeV/nucleon during the Maunder Minimum). Fig. 1 displays the ^{10}Be data from Dye 3, Greenland (65.2°N; 43.8°W), for the period 1423–1978, and shows that the concentration of ^{10}Be was high in the ice corresponding to the Spoerer Minimum (1420–1520), the end of the Maunder (1680–1720) and Dalton (1810–1820) Minima in sunspot activity. These enhancement events commence and end abruptly, and in each case the ^{10}Be concentration increases by 30–50% above the prevailing values. However, the observed concentration of ^{10}Be is determined by both production and atmospheric transport processes, and a terrestrial origin for the enhanced values in Fig. 1 is possible. All three enhancements occurred during the "little ice ages" and it has been suggested (Lal, 1987) that the enhanced values of ^{10}Be are the result of climatic factors, such as a reduced precipitation of snow. To date, this uncertainty has inhibited the use of these data in the inverse problem – i.e., the quantitative study of the time variations of the galactic cosmic radiation (GCR), and has allowed discrepancies between theoretical predictions and the ^{10}Be data to be ignored.

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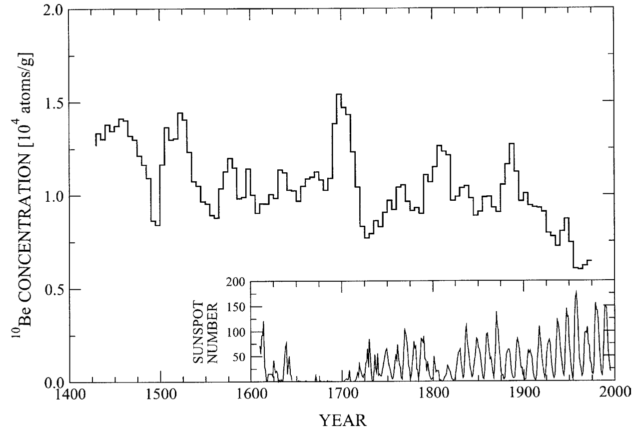

Fig. 1. The 11-year average ^{10}Be concentration observed in Greenland, and the group sunspot number (McCracken, 2004).

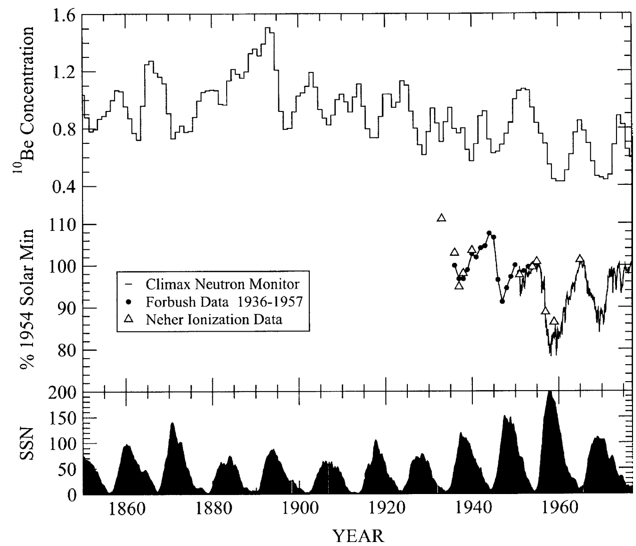

Fig. 2. The annual ^{10}Be concentration observed in Greenland after application of a (1,2,1) binomial filter. The middle graph presents the Climax neutron data, 1951–1984, and the estimated neutron monitor response 1933–1954, based on the ground level ionization chambers of S.E. Forbush, and the balloon borne ionization chambers of Neher (see text).

Examination of Fig. 1 shows that there are enhancements in the ^{10}Be data during the interval 1890–1895, and prior to the sunspot minimum of 1954 that are of similar character to those during the Maunder and Dalton minima. The enhancement of 1954 is smaller than the other three (26% enhancement compared to 50%), and has not been studied previously. Neither period has been identified as a "little ice age"; consequently a meteorological origin as suggested for the earlier enhancements appears unlikely. Instrumental recording of the cosmic radiation commenced in the 1930s, and this allows an independent test whether the enhanced values of ^{10}Be in the vicinity of 1954 are the consequence of enhanced cosmic ray fluxes. This paper shows that the instrumental data verify that the low energy cosmic radiation flux was substantially higher in the interval 1951–1954 than in 1965 and 1976, and then the instrumental and ^{10}Be data are used together to estimate the spectrum of the galactic cosmic radiation during the 1954 enhancement event. Other features of the 1954 enhancement are then examined, leading to a discussion of the nature of the cosmic ray modulation in the vicinity of 1954. The spectra of the GCR during the enhancements of 1890–1895, and the Maunder and Dalton minima are estimated, and used to estimate the ionization in the polar atmosphere during all four events.

2. Comparison of the ^{10}Be data with the instrumental record

Fig. 2 presents the annual ^{10}Be data for the interval 1850–1977, together with representative instrumental data starting in 1933. The earliest instruments were ionization chambers; between 1933 and 1965 Neher and his co-workers made a series of high altitude ionization chamber measurements in which the ionization rate was measured as a function of atmospheric depth from sea level to a pressure of about 15 g/cm^2, and after 1951, to 5 g/cm^2. A set of calibration chambers was used for pre flight calibration throughout the 32 year program, and inter-calibration accuracy was stated to be better than 1% (Neher et al., 1953). Apart from the laboratory calibrations, this accuracy was repeatedly verified by making duplicate flights throughout the 32 year program. Furthermore, unlike the ground level chambers (see below), the inescapable time dependent errors due to minor radioactive contamination were small compared to the cosmic ray ionization rate at high altitudes. Examples of Neher's data are given in Figs. 3 and 4. Note that Fig. 3 is for Bismarck, South Dakota, where the geomagnetic cutoff is 1.29 GV, while Fig. 4 is for Thule, Greenland, where the geomagnetic cutoff is ~0 GV. As a consequence, galactic cosmic ray protons with energy $E < 630$ MeV contribute to the ionization at Thule, but not at Bismarck. This will be discussed further in Section 3.

A network of ground level ionization chambers was established in 1936 (Forbush, 1958). The ionization current due to radioactive contamination of the chamber itself and it's surrounds is considerable, and it decays with time. For example, it changed by 6% in the Huancayo (Peru) ionization chamber over the period 1938–1954, compared to the 4–5% amplitude of the 11-year variation (Forbush, 1958). Forbush removed these drifts wherever possible, however substantial long-term drifts remain in his adjusted data. The good calibration accuracy of the Neher data has been used by McCracken and Heikkila (2003) to minimize the long term drifts

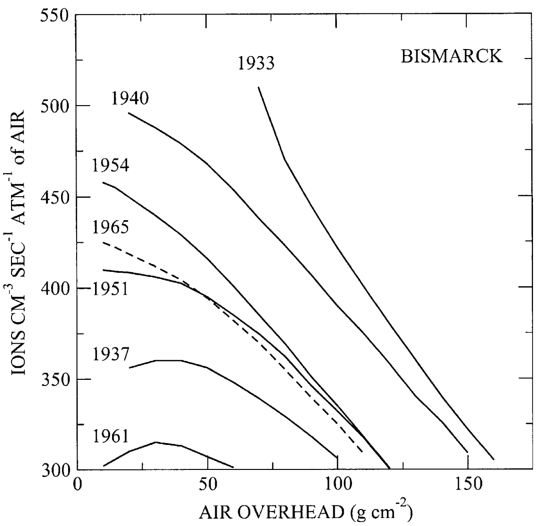

Fig. 3. The observed cosmic ray ionization versus atmospheric depth during the interval 1933–1965 at Bismarck, South Dakota, where cosmic ray protons <630 MeV are excluded by the geomagnetic field.

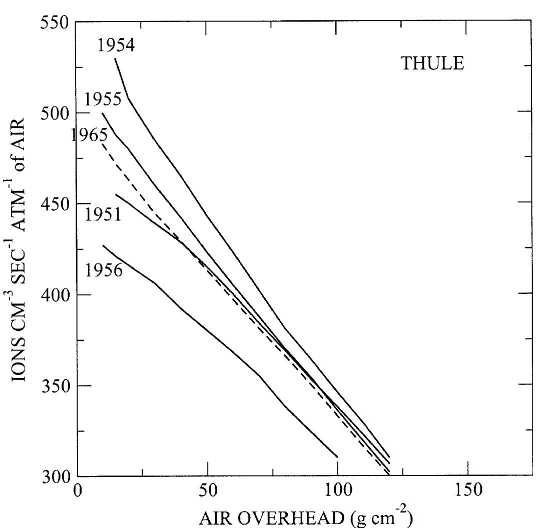

Fig. 4. The observed cosmic ray ionization versus atmospheric depth at Thule, Greenland, where all cosmic rays gain access down to the height dependent atmospheric cutoff (e.g., 138 MeV at 15 g/cm^2).

in the Forbush data, and the ionization chamber data were then converted to the equivalent variations in the neutron data. Their estimated time dependence of the neutron monitor intensity prior to 1954 is displayed in Fig. 2.

Considering the interval 1933–1977 in Fig. 2, we note that the 11-year variation of the galactic cosmic radiation is well defined in both the ^{10}Be and the neutron records. The variations in the ^{10}Be data are of amplitude ~40%, and ~15% in the neutron data. This difference is quantitatively consistent with the results of McCracken (2001, 2004) who has shown that the ^{10}Be data correspond to lower energy cosmic rays than does the ground level neutron monitor.

Examining the longer term trends in Fig. 2, the ^{10}Be concentration declined from ~1.2×10^4 atoms/g for the sunspot minima of 1889 and 1901, to ~0.8×10^4 atoms/g for the sunspot minima of 1965 and 1976. This appears as a relatively steady decline in the 11-year average data in Fig. 1. The middle plot in Fig. 2 shows that the estimated cosmic radiation intensity decreased substantially between the sunspot minima of 1933, 1944, and 1954, and remained approximately constant thereafter. To verify that this is not an artifact of the process used to estimate the neutron intensity, 1933–1954, we note that the Neher ionization measurements from Bismarck for 1940 (at an atmospheric pressure of 100 g/cm^2, Fig. 3) were ~16% above those for the sunspot minimum of 1954, even thought the 1940 measurements were made >3 years before the sunspot minimum of 1944. Furthermore, Fig. 2 shows that the Neher data for 1936 (a year prior to the solar maximum of 1937) was approximately equal to that for the sunspot minimum of 1954. Clearly, there was a long-term decline in the instrumental measurements between 1933 and 1954, upon which the 11 year modulation was superimposed.

In summary, the instrumental data verify that there was a long term declining trend in the galactic cosmic ray intensity prior to 1954, as indicated by the ^{10}Be data in Fig. 1. It is noted that Neher (1967) clearly stated that there had been a steady and substantial decline in the galactic cosmic radiation intensity between the sunspot minima of 1933, 1954 and 1954; however, it appears that his discovery has been forgotten with the passage of time.

3. The 1954 enhancement

As discussed in Section 1, Fig. 1 shows that the almost monotonic decline between ~1895 and 1965 was interrupted by an enhancement in the vicinity of 1950. Examination of the cosmic ray and ionospheric data for that interval indicates that this was not due to the generation of cosmic rays by the Sun. The 11 year average ^{10}Be in the vicinity of 1950 was ~26% greater than that in 1965, and we will now verify that this is consistent with the instrumental measurements. The annual data in Fig. 2 shows that this increase appears as a 20–28% enhancement of the ^{10}Be concentration for the several years prior to the sunspot minimum of 1954, relative to those of 1944 and 1965. Note, however, that the cosmic ray intensity recorded by the Climax neutron monitor for 1954 is approximately equal to that of 1965 in Fig. 2. This has been used previously to infer the presence of meteorological or other measurement uncertainties in the ^{10}Be data; however we will now show that it is the consequence of historical factors at the beginning of the neutron monitor era. The first continuously recording neutron monitor was established at Climax, Colorado, in 1951, and its data are given in Fig. 2. The cutoff rigidity at Climax was 3.15 GV; that is, cosmic ray protons of energy <2.3 GeV were excluded by the geomagnetic field. The specific yield function for ^{10}Be peaks in the range 1–2 GeV; that is, the cosmic rays that make the greatest contribution to the ^{10}Be production at Earth cannot reach Climax. To validate the ^{10}Be enhancement, we need to use data that are sensitive to the lower energies (>500 MeV) that make the greatest contributions to the observed ^{10}Be data.

Thule, Greenland, has a geomagnetic cutoff of ~0 GV, and it therefore samples all of the energies that contribute to ^{10}Be production. The ionization data in Fig. 4 shows that the altitude curve at ~15 g/cm^2 at Thule was 15% higher in 1954 than at the same location in 1965. Neher (1967) attributed this to an additional influx of <800 MeV protons during the 1954 sunspot minimum, in qualitative agreement with the ^{10}Be data. Unlike the Climax neutron monitor, Mt. Washington, New Hampshire, has a geomagnetic cutoff of 1.24 GV (593 MeV protons), and it therefore samples the energies that contribute to the production of ^{10}Be. A neutron monitor was established at Mt. Washington, New Hampshire in 1954, and Fig. 5 shows the cosmic radiation data from this monitor plotted versus the Neher ionization chamber data from Thule for the solar cycle 1954–1965. A good correlation is evident, and both data are in good agreement that the cosmic ray intensity was significantly higher in 1954 than in 1965. The observed differences between 1954 and 1965 vary widely however, from 26% for the ^{10}Be data, to ~3–4% for the cosmic radiation intensity measured by the neutron monitor. We now show that these differences are consistent with the different energy sensitivities of the measurements.

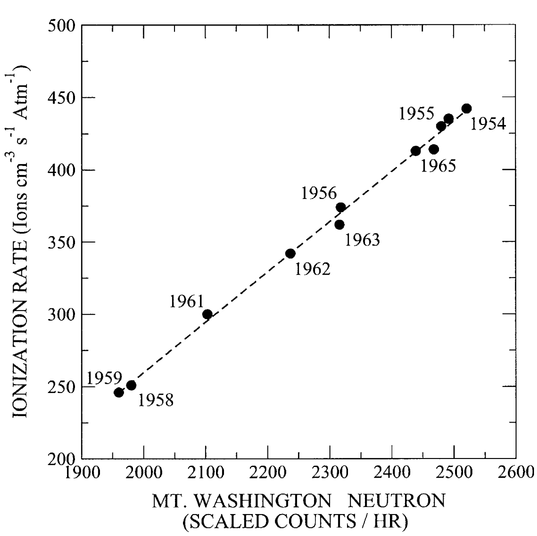

Fig. 5. The cosmic ray ionization rate observed at Thule (geomagnetic cutoff ~0 MeV) at an atmospheric pressure of 50 g/cm^2, plotted against the Mt. Washington neutron monitor counting rate averaged over the 6 h centered on the time the balloon reached its peak altitude.

Fig. 6 presents the estimate of the local interstellar spectrum (LIS) of galactic cosmic ray protons outside of the heliosphere (Webber and Lockwood, 2001)—that is, prior to modulation by the heliospheric magnetic fields. It also gives the observed spectrum of protons for 1965, as assembled from a number of different sources by Webber and Lezniak (1974). The Neher (1967) values for the proton fluxes in 1954 and 1965 are superimposed thereon. From this it is clear that (1) there is good agreement between the flux estimates made by Neher for 1965, and the independent data assembled by Webber and Lezniak (1974); and (2) that the galactic cosmic ray proton flux in the energy range 0.15–0.35 GeV for 1954 was significantly above the peak values observed in 1965 and 1976 (see Fig. 2).

Our present understanding of cosmic ray modulation is based upon the motion of charged particles in the interplanetary field as described by the cosmic ray transport equation (Parker, 1965). Based on that equation, the force field modulation function, Φ, was defined by Gleeson and Axford (1968). Subsequently, the heliospheric current sheet was identified, and it was found that its inclination to the solar equator changed from 0° at sunspot minimum, to near 90° at solar maximum. The gradient and curvature drifts in the interplanetary magnetic field have a major influence on the motion of the cosmic rays in the heliosphere, and are major contributors to the 11-year variation (Jokipii and Thomas, 1981; Potgieter and Le Roux, 1992). These effects are not included in the concept of the modulation function; nevertheless Φ is frequently used as an quasi-empirical formalism that gives a useful phenomenological de-

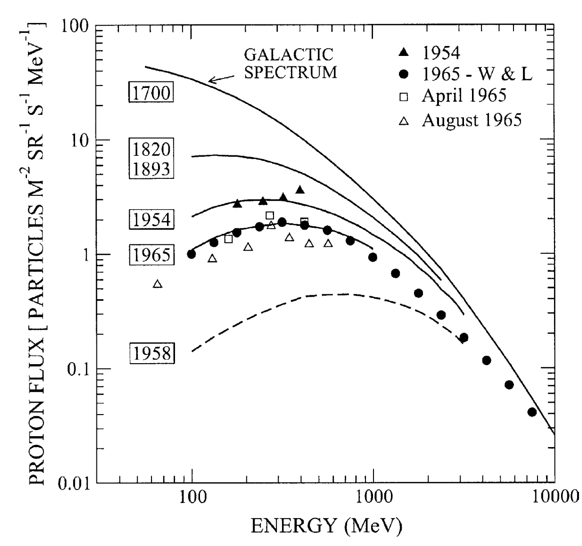

Fig. 6. The energy spectra of cosmic ray protons deduced by Neher for 1954 (solid triangles) and 1965 (open symbols). The solid circles are other measurements of the proton spectrum in 1965. The local interstellar spectrum of Webber and Lockwood (2001) is indicated by "galactic spectrum". The lower four curves are the spectra estimated for the years indicated (see text).

scription of the rigidity and energy dependence of the 11-year modulation of the galactic cosmic radiation near Earth. It is used in that role herein to compare the modulation at sunspot minimum (i.e., when the tilt angle of the heliospheric current sheet approximates 0° and has the least effect upon the cosmic ray modulation).

Using the Webber and Lockwood (2001) galactic spectrum in Fig. 6, the values of the modulation function, Φ, giving a fit to the Webber and Lezniak data for 1965 and the Neher data for 1954 were calculated (Table 1), the resulting modulated spectra being shown in Fig. 6. Any cosmic ray measurement $G(t)$ is related to the primary spectrum $J(E)$ by an equation of the form

$$G(t) = \int S(E)J(E)\,\mathrm{d}E, \tag{1}$$

where $S(E)$ is the specific yield function, and the integration is from the geomagnetic cutoff to infinity (Clem and Dorman, 2000). Using this equation, the neutron monitor counting rates and ^{10}Be fluxes corresponding to the $\Phi = 300$ and 430 MV spectra in Fig. 6 were computed, using the Nagashima et al. (1989) specific yield functions for a high latitude neutron monitor and a ^{10}Be specific yield function derived by McCracken (2001) from the calculations of Masarik and Beer (1999) that also includes an allowance for the alpha and heavy component of the galactic cosmic radiation. These calculations predict differences of 3.4% and 19% for neutron monitor and ^{10}Be data, respectively, for the spectral change between $\Phi(1954) = 300$ MV, and $\Phi(1965) = 430$ MV.

The ^{10}Be data in Fig. 2 are weighted averages over three years (weights = 0.25, 0.5, 0.25). Fig. 1 shows that there were significant long term and short-term variations in the cosmic ray flux during this period. In particular, the 1954 cosmic ray maximum has a "flat top"; while that of 1965 has a "pointed" top, as a result of the effects of particle drifts (Jokipii et al., 1977). This systematic difference between the two cosmic ray maxima means that the ^{10}Be weighted average will exhibit a larger excess of 1954 over 1965 than implied by the differences between the "instantaneous" spectra in Fig. 6. To allow for this, Eq. (1) was used to compute the dependence of the neutron monitor counting rate on Φ; from this, the Climax neutron monitor data were used to estimate Φ as a function of time throughout 1952–1955 and 1963–1966; and then the weighted averages of Φ were calculated corresponding to the 1954 and 1965 average ^{10}Be data. Using these weighted mean Φ values, Eq. (1) yields a ^{10}Be concentration for 1954 that is 24% above that for 1965, as given in Table 1. In the case of the neutron monitor data the enhancement in Table 1 is computed for the 6 h centered on Neher's balloon flights. Table 1 shows that the spectral difference inferred from the Neher measurements predicts differences in the Mt. Washington and ^{10}Be data that are in agreement with the observations to within the statistical errors.

The ionization chamber and neutron monitor data therefore verify that the 1954 enhancement in ^{10}Be concentration was due to an increase in the intensity of the low energy galactic cosmic radiation, and that no other factors (e.g., meteorology) are required to explain the ^{10}Be observations. This is an important result, since it provides confidence other fluctuations of similar amplitude in Fig. 1 may be due to changes in the intensity of the galactic cosmic radiation. As such, this validation of the ^{10}Be data by the instrumental record 1933–1965 provides a basis for using the ^{10}Be data to investigate the temporal variation of the GCR prior to the commencement of the instrumental record.

As noted in Section 1, the enhancement of 1954 has similarities to those associated with the Gleissberg minimum (~1895), and the Dalton and Maunder Minima (see Fig. 1). Using Eq. (1), and the ^{10}Be specific yield function, we have computed the values of the modulation potential, Φ, which yield the observed average

Table 1
Characteristics of the four ^{10}Be enhancements in the galactic cosmic radiation

Enhancement date	1680–1720	1810–1820	1893–1895	1954	1965
Annual Z_{min}	0	0	2.5	4.4	10.2
Modulation potential	→0	150	150	300	430
Predicted					
^{10}Be	100%	50%	50%	24%	0%
Neutron			4.2%		
Observed					
^{10}Be	100%	53%	53%	26%	
Neutron			3.6%		

The quantities tabulated are defined in the text. The ^{10}Be data for 1954 and 1965 are 3-year averages with weights of 0.25, 0.5, 0.25. For the earlier enhancements, they are averaged over the whole enhancement. The measurement errors of the ^{10}Be and neutron monitor data are 7% and 0.5%, respectively. The symbol →0 means approaching zero. The group sunspot number for the 1893–1895 event refers to the subsequent sunspot minimum of 1901. The predicted and observed values of ^{10}Be concentration, and neutron monitor counting rate, are relative to 1965. As described in the text, the ^{10}Be prediction makes allowance for the temporal variations in the GCR over the averaging period used for the ^{10}Be data.

values of the ^{10}Be concentrations for the three earlier enhancement events in Fig. 1. These are given in Table 1, and the corresponding cosmic ray spectra are displayed in Fig. 6.

4. Correlation with solar activity

Table 1 lists the annual sunspot numbers at sunspot minimum (Z_{min}) for the four ^{10}Be enhancements in Fig. 1 for which sunspot data are available. To provide better comparability throughout the 400 years, this paper uses the "group sunspot numbers" of Hoyt and Schatten (1998). In so doing, we are using the sunspot number as a proxy for solar activity (for example, Webb and Howard (1994) have found a strong linear correlation between sunspot number, and coronal mass ejections). As discussed in Section 1, the ^{10}Be enhancement events in 1680–1720, and 1810–1820 are both associated with $Z_{min} = 0$ during the Maunder and Dalton minima. Table 1 shows that the enhancement events of 1890–1895 and 1954 also occur in proximity to low values of Z_{min}. In the case of the 1954 ^{10}Be enhancement, the sunspot numbers for the maximum of the sunspot cycle immediately after it were the highest in recorded history, while the previous cycle was the fourth largest, indicating that this was a period of exceptional solar activity. Nevertheless, the annual sunspot number at the 1954 minimum was one of the lowest (4.4) recorded outside of the Maunder and Dalton minima. To emphasize the unusual nature of the 1954 minimum – the Z_{min} for the solar minima of 1944, 1965, 1976, and 1986 were 10.7, 10.2, 13.5, and 12.1, respectively, being the four highest values for sunspot minimum in the whole 400-year sunspot record. In the case of the 1890–1895 ^{10}Be enhancement, $Z_{min} = 2.5$ at the subsequent sunspot minimum of 1901.

To further explore the correlation with Z_{min}, Fig. 7 plots the annual ^{10}Be concentration (from Fig. 2) against Z_{min} for each of the sunspot minima between 1901 and 1986. A well defined anti-correlation is evident. Note, in particular, that the point for 1954 is in close proximity to those for 1901 and 1913. Examining the point to point changes, Z_{min} increased from ~2 near 1900, to 10.2 in 1944. It then returned to a low value in 1954 (4.4); followed by a series of high values >10 starting in 1965. 1954 is anomalous in the ^{10}Be data as well, attaining a value that was ~26% above the values for the maxima in the vicinity of 1944 and 1965. Note further that there is no phase lag between the reduction in Z_{min} and the increase in the cosmic ray flux. The anomalous nature of 1954 in Fig. 7; the anti-correlation in general; and the absence of a phase lag; indicates that the cosmic ray modulation mechanism at sunspot minimum is controlled by a factor that is well correlated with the concurrent value of Z_{min}. The change in annual ^{10}Be concentration between 1901 and 1965 is $\sim 0.4 \times 10^4$ atoms/g, while it is typically $\sim 0.4 \times 10^4$ atoms/g over a sunspot cycle. This shows that the change in modulation conditions associated with the relatively small changes in Z_{min} represents a major effect, which is comparable to the modulation that occurs during the sunspot cycle.

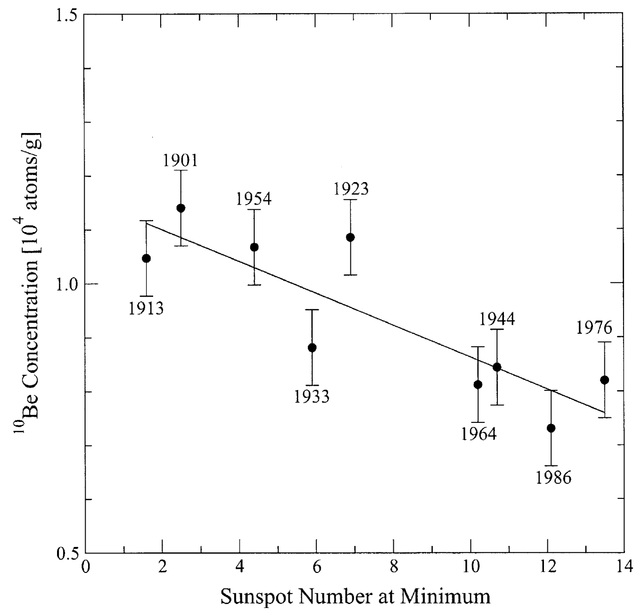

Fig. 7. The ^{10}Be concentration plotted against the annual group sunspot number for the sunspot minima 1901–1986. The ^{10}Be concentration is averaged over three years using a (1,2,1) binomial filter.

The above discussion has shown that the sunspot minimum of 1954 was anomalous in two respects; (1) the flux of low energy galactic cosmic radiation was considerably greater than at any of the subsequent sunspot minima; and (2) the sunspot number at solar minimum was one of the lowest in recorded history. The year 1954 was anomalous in a yet another way that may provide considerable insight into the cosmic ray processes at the time. First Forbush (1969), then Bieber and Chen (1991) showed that the "free space" phase of the diurnal anisotropy exhibits a 22-year variation. It remained close to 1800 h (i.e., the flow vector was in the direction of Earth's orbital motion) for the majority of the period 1936–1988, while moving to the vicinity of 0800 and 1300 h for the qA>0 sunspot minima of 1954 and 1976 (ionization chamber data), respectively. The diurnal anisotropy indicates the direction of cosmic ray flow in the vicinity of Earth, and a phase of 0800 h indicates that the flow was outwards along the Parker spiral from the Sun. The diurnal anisotropy is driven by the spatial gradients in the cosmic ray density, and the 1954 result indicates that there was a negative gradient in the vicinity of Earth in 1954.

5. Discussion

5.1. Solar implications

As discussed in Section 3, the modulation of the galactic cosmic radiation flux is described by the cosmic ray transport equation (Parker, 1965). This shows that the polarity of the heliomagnetic field determines the direction of the cosmic ray drift motions, and that during the sunspot minimum of 1954, the cosmic rays reached the vicinity of Earth by entering the heliosphere at high solar latitudes; propagating to the ecliptic via curvature and gradient drift motions (Jokipii et al., 1977) and then being convected out of the solar system by the solar wind. The cosmic ray drift motions are most efficient in well ordered magnetic fields; a decrease in the scattering properties of the heliospheric magnetic fields will increase the drift velocities, leading to more efficient transfer of the cosmic rays from above the solar poles, to the vicinity of Earth. Thus, a decrease in the scattering properties of the heliospheric magnetic fields (i.e., large values of the transverse diffusion mean free path, λ_{perp}) could explain the enhanced intensity of GCR in 1954. This could also imply that the cosmic ray density gradient would be negative in the inner solar system (H. Moraal, private communication), and this would have the diagnostic implication that the diurnal cosmic ray anisotropy would flow outwards along the Parker spiral. As summarized in the previous section, 1954 was the only year when the diurnal anisotropy was so aligned (Forbush, 1969; Bieber and Chen, 1991). We propose that the three independent observations of the 1954 enhancement (^{10}Be, balloon ionization chamber, and neutron monitor), and the anomalous diurnal variation, support the hypothesis that the heliospheric magnetic fields allowed the galactic cosmic rays to reach the Earth with relative ease during the $\mathrm{qA} > 0$ sunspot minimum of 1954 via high polar latitudes of the Sun.

To further understand the solar conditions in 1954, we have examined the daily sunspot numbers, Z_{d}. Starting abruptly in early November, 1953, Z_{d} decreased to zero, and was identically zero for >80% of all the days in the eight following months, except March, 1954. During 1953, the Climax neutron monitor counting rate had been increasing steadily at 1% per year. Starting in November 1953, it rose rapidly by 3%, and remained at that high level for the 8-month period of $Z_{\mathrm{d}} \cong 0$. For the remainder of 1954, the neutron monitor exhibited a large amplitude 27 day variation, returning to the high values of July 1954 whenever $Z_{\mathrm{d}} = 0$ for >10 days. This provides further evidence of the substantial changes in modulation associated with very low values of the sunspot number, as first recognized in Fig. 7.

As discussed above, it appears possible that the inverse correlation in Fig. 7 is due to an association between low (and zero) sunspot number at solar minimum, and high values of λ_{perp}. There are usually few sunspots visible at sunspot minimum; they are small; and usually confined to a single Carrington longitude. Consequently it is not a priori evident that a low sunspot number could provide any information about the extended three dimensional region that influences the galactic cosmic radiation flux. Fig. 7 therefore conveys the important result that the sunspot number is providing a proxy for the magnetic conditions over a substantial region of space at sunspot minimum.

A number of phenomenological models have been developed for the time dependence of the Sun's magnetic field based upon diffusive and convective transfer of magnetic field from the active sunspot regions to the "open" field that permeates the expanding solar wind (Solanki et al., 2000, 2002; Schrijver et al., 2002, and references therein). A different, more theoretical approach by Fisk and Schwadron (2001) implies a smaller variation in the open flux over a solar cycle. The calculations of Solanki et al. and Schrijver et al. show that the solar open magnetic flux at sunspot minimum would increase in a monotonic manner through 1954. Lockwood et al. (1999) used the geomagnetic "aa" index to estimate the strength of the interplanetary magnetic field (IMF), and also inferred that the sunspot minimum value increased steadily between 1901 and 1954. All three sets of authors concluded that the strength of the interplanetary magnetic field (IMF) at sunspot minimum had increased in a monotonic manner by a factor of >2 between the minima of 1901 and 1954. They then made the assumption that the galactic cosmic ray flux is inversely proportional to the strength of the IMF, and used the decline in GCR flux, as recorded in the ^{10}Be data, to validate their models. None recognized the existence of the ^{10}Be enhancement in 1954, and it's impact on their argument.

Fig. 7 shows that the ^{10}Be data returned to the 1901 levels for the single sunspot minimum of 1954, and with no discernable phase lag. On the basis of the argument used by the above authors, this would imply that the IMF decreased by a factor of two between 1944 and 1954, and then increased by a factor of two between 1954 and 1965. Both the Solanki et al. (2000, 2002) and Schrijver et al. (2003) models have a "memory"; the IMF at any time is determined by the magnetic flux contributed by the Sun over previous solar cycles, and consequently the IMF cannot change rapidly. A factor of two decrease in IMF in 1954 is not predicted by their models, and the enhancement of 1954 therefore either (1) demonstrates that the models for the IMF are incorrect; or (2) that there is a shortcoming in the process they used to validate their models.

As discussed above, the modulation of the galactic cosmic radiation flux is described by the cosmic ray transport equation (Parker, 1965). The depth of modulation at sunspot minimum is determined by several factors, including the turbulence spectrum and speed of the solar wind; and the diffusion and transport coefficients for the diffusion and drift motions of the cosmic rays in the IMF. To a first approximation, the diffusion and transport coefficients are inversely proportional to B, the magnetic induction of the IMF. In assuming that the GCR flux was inversely proportional to B, the above authors have assumed that the turbulence spectrum and speed of the solar wind were invariant over the period 1901–1954. There is no evidence to support that assumption. As shown above, the enhancement of 1954 and the associated anomalous diurnal anisotropy are consistent with a substantial yet short-lived increase in λ_{perp}. The very low solar activity at the time could mean that there was less turbulence in the solar wind, and not require low values of B. That is, the apparent disagreement with the analyses of Lockwood et al. (1999), and the models of Solanki et al. (2000, 2002) and Schrijver et al. (2002), can be avoided by abandoning their implicit assumption that the GCR flux is inversely correlated with B alone.

5.2. Terrestrial implications

Neher's observations show that the flux of 0.15–0.35 GeV protons entering the polar caps in 1954 was a factor of two greater than that in 1965. Using the spectra for 1954 and 1965 given in Fig. 6, and Neher's ionization versus height curves, we have computed the yield function, $S(E)$, for a balloon borne ionization chamber. Using Eq. (1), and the spectra in Fig. 6, we have then computed the ionization versus height curves presented in Fig. 8.

As a low energy cosmic ray approaches the end of its range, its ionization rate increases rapidly. At heights above 100 g/cm^2, this results in each cosmic ray generating a column of ionization, >100 m long, with ionization densities greater than ten times the minimum ionization rate. For the purpose of this paper we choose to emphasise this feature of the cosmic ray ionization in the upper polar atmosphere. To this end, Fig. 8 quantifies the production of dense tracks versus height, and time. Fig. 6 predicts that the change in cosmic ray flux was large (up to a factor of 30) at low energies between 1700 and 1965, and the consequence is clearly evident in Fig. 8. For example, at 10 g/cm^2, we deduce that the occurrence rate of dense tracks was 30 times greater in 1700, than in 1965. At 100 g/cm^2, the factor decreases to five.

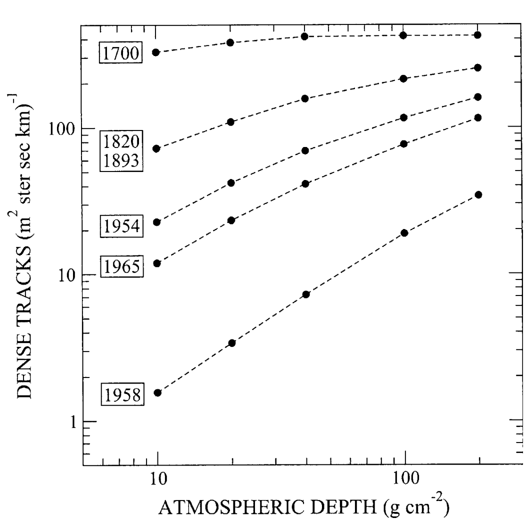

Fig. 8. The cosmic ray ionization rate in the atmosphere versus atmospheric depth (i.e., pressure). The curves for 1954, 1958, and 1965 are computed from the observations made by Neher (1967). The curves for 1700, 1820 and 1893 were computed using the spectra in Fig. 6.

A number of mechanisms have been proposed whereby the ionization produced by the cosmic radiation might affect the condensation of water droplets (Ney, 1959; Svensmark and Friis-Christensen, 1997; Tinsley, 2000). Fig. 8 predicts that the ionization rate in 1700 was higher than that in 1965 by factors in the range 5–30. Note, however, that these increases in ionization are greatest at high latitudes (the geomagnetic cutoff effect), and high altitudes, in disagreement with the analysis of Svenmark and Friis-Christensen which showed that the 11 year enhancements in cloudiness occurred at low latitudes and low altitudes. The increases in ionization in Fig. 8 are large, and it appears possible that there may be forcing a mechanism that produces a climate response in a way that has not been recognized yet.

6. Conclusions

1. The long and short term variations in the Dye 3 cosmogenic ^{10}Be record are in quantitative agreement with the instrumental measurements of the cosmic radiation made in the interval 1933–1977, and confirm that the ^{10}Be data provide a reliable measure of the galactic cosmic ray intensity at Earth.
2. The instrumental records with low geomagnetic cutoff energies confirm that the short lived 26% enhancement in the ^{10}Be concentration in the vicinity of 1954 was due to a variation in the low energy cosmic ray flux. This provides confidence that the ^{10}Be concentration provides a reliable measurement of relatively small changes in the cosmic ray flux at times prior to the commencement of instrumental measurements.
3. The balloon borne data (1933–1965), and the cosmogenic ^{10}Be data show that the modulation potentials corresponding to the peak values of the GCR intensity since 1600AD were; approaching zero for the Maunder Minimum; ~150 MV for both the Dalton Minimum and the minimum of the Gleissberg cycle (1895), and −300 MV for the 1954 enhancement.

4. The ^{10}Be enhancement event of 1954 occurs simultaneously with (a) one of the lowest values of Z_{min}, the sunspot number at sunspot minimum, in the 400-year historical record, and (b) the observation of an anomalous cosmic ray diurnal variation throughout 1954. The latter indicates that in the vicinity of the orbit of Earth, there was a net outward flux of cosmic radiation along the Parker spiral direction of the interplanetary magnetic field. This is the only such case in the instrumental record, 1936–1988.
5. Over the period 1900–1984, there was a negative correlation between the ^{10}Be concentration at sunspot minimum, and Z_{min}. The amplitude of the change in ^{10}Be concentration corresponding to a change in Z_{min} from 2.5 to 10 approximates the change throughout the 11-year cycle.
6. We propose that the 1954 enhancement is a consequence of the well known drift effects in the heliosphere. 1954 was a $qA > 0$ sunspot minima; cosmic rays were entering the heliosphere at high solar latitudes and reaching Earth by gradient and curvature drift motions. The ^{10}Be enhancement, and the anomalous diurnal variation are both consistent with relatively rapid access of the cosmic radiation via these drift motions compared to other $qA > 0$ minima (1933, 1976, 1997). We propose that this implies a relatively ordered heliospheric magnetic field, with relatively high values of the transverse diffusion mean free path, λ_{perp}. We further speculate that low values of Z_{min}, may provide a useful proxy for λ_{perp} at sunspot minimum.
7. We conclude that the enhancement event of 1954 demonstrates shortcomings in the methods used by Lockwood et al. (1999), Solanki et al. (2000, 2002) and Schrijver et al. (2003) to validate their models of the strength of the open solar magnetic field. We conclude that those methods were deficient in that allowance was not made for the effect of heliospheric parameters other than B in the comparisons with the cosmogenic ^{10}Be data. For example, we show that failure to do so leads to the conclusion that the strength of the IMF increased by a factor of two from 1933 to 1954, this being contrary to the predictions of all three models.
8. The direct observations made by Neher, and the projections made herein, have been used to estimate the ionization distribution in the polar atmosphere during the periods of high cosmic ray intensity in 1890–1895, and during the Dalton and Maunder minima. We compute that in 1700 the occurrence of densely ionized tracks in the polar atmosphere was ~30 times that in 1965 at a pressure of 10 g/cm^2. This difference declined with atmospheric depth; e.g., it was a factor of five greater in 1700 at a pressure of 100 g/cm^2.

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