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The long term modulation of the galactic cosmic radiation, 1500-2000

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Abstract. The temporal variations of the cosmogenic isotope ^{10}Be for the period 1500-2000AD are used to investigate the nature of the cosmic ray modulation process, and the properties of the cosmic ray spectrum outside the heliosphere. It is shown that the cosmic radiation observed at earth has been subjected to a long term modulation mechanism with a relaxation time ≥ 200 years, in addition to the 11 year modulation. It is proposed that this modulation occurs within the heliosheath. The 200 year modulation has depressed the spectrum at ~2GeV by >50% since 1695; making it 2.5-3 times greater than the 11 year modulation events observed since 1954. The ^{10}Be data in the vicinity of 1695 are too high to be explained by the force field modulation function, and there is a speculative argument that the ^{10}Be concentration could be a further 63% higher in the total absence of modulation. In view of its large amplitude, however, use of the Gleeson and Axford modulation function in its description is likely to result in substantial errors. It is proposed that the high values of ^{10}Be in 1695 should be used as a constraining measurement, together with the energy and isotopic spectra observed near earth, in the determination of the properties of the local interstellar cosmic ray spectrum.

1 Introduction

Careful study of the cosmogenic isotopes ^{14}C and ^{10}Be has established that they exhibit substantial time variations associated with changes in the cosmic ray intensity. This paper and its companion (McCracken, 2001) reverse that process, and use the cosmogenic data to extend our knowledge of the cosmic ray modulation processes themselves, and to investigate the properties of the cosmic ray spectrum outside the heliosphere.

We use ^{10}Be for this initial investigation because it precipitates to earth within about one year, and has none of the attenuation and phase lag effects encountered with ^{14}C.

2 Analytical Procedure

Figure 1 displays ^{10}Be data from several sources for the period 1500-2000AD. The period 1784-1976 uses the time averaged data from "Dye 3" in Greenland (65 N) as given in Fig 1b of Beer et al (1990). The period 1500-1780 is based upon a data synthesis using data from Millicent (70°N, Greenland), and the South Pole (Beer et al, 1992; Bard et al, 1997). The ^{10}Be concentrations for Dye 3 were given by Beer et al (1990) in the conventional units of 10^4 atoms per gram, as used here. In the case of the synthesis for 1500-1780 the data were given as a variation relative to the mean for the interval 1000-1800, and this was normalized to the Dye 3 data using the overlapping period 1784-1800. The standard deviations shown throughout this paper are derived from the statistical analysis outlined in McCracken (2001).

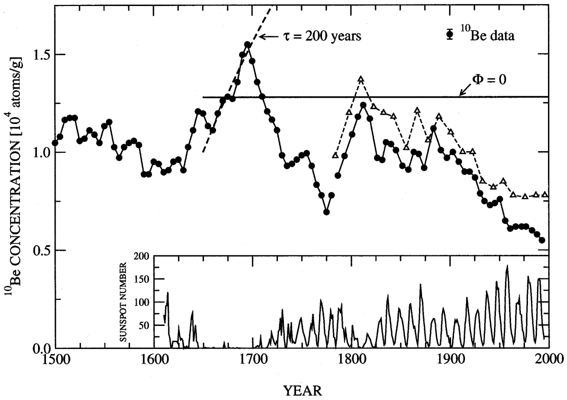

Fig.1 The observed concentrations of ^{10}Be, 1500-1975, and the group sunspot number. The triangles give the sunspot minimum values after 1784, and the solid circles approximate the averages over the sunspot cycle. The points after 1975 are estimated from neutron monitor data. The ϕ = 0 line is the estimate of the ^{10}Be concentration when the modulation potential equals zero. The dotted line 1650- 1720 is the 200year exponential recovery described in the text.

The concentration of ^{10}Be measured in ice cores is influenced by four major factors; (1) the production rate of the ^{10}Be which is a strong function of latitude; (2) mixing and redistribution of the ^{10}Be in the atmosphere; (3) the ^{10}Be precipitation process; and (4) variable dilution by time changes in the annual snow fall, and "reworking" of the surface snow. The first two factors have been considered in McCracken (2001), and this paper uses the important result obtained there that the ^{10}Be precipitated at all three locations has originated in the polar atmosphere. The latter two factors are addressed below.

The right hand scale in Fig. 1 displays the values of the force field modulation function, ϕ, that corresponds to

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the concentration scale on the left. This equivalence has been derived as follows. Since the sunspot minimum of 1954, the cosmic ray intensity >1 GeV/nucleon has been essentially the same at all succeeding sunspot minima (see McDonald, 1998, and references therein). Many workers have analyzed neutron monitor and satellite time series, and balloon and satellite energy spectra during these minima, and there has been wide agreement that ϕ = 450-500MeV provides the best fit to the observed sunspot minimum data. The average ^{10}Be concentration for the sunspot minima of 1954, 1965, 1976 is 0.78 x 10^4 atoms/gram; associating that value with ϕ = 440 MeV (Lukasiak, personal communication); and using the production rate data from Figs. 8 and 9 of Masarik and Beer (1999); the ^{10}Be concentrations corresponding to the various values of ϕ were determined. This calculation requires knowledge of the latitudes that contribute to the observed ^{10}Be, and the result that polar production dominates at all three locations (McCracken, 2001, and references therein) was used here.

3 The cosmic ray variation, 1500-2000AD

As noted above, the measurements made with neutron monitors, balloons, and satellites have all agreed that the cosmic ray intensity has returned to essentially the same asymptotic value during each sunspot minimum between 1954-1997. Therefore, the most striking feature of Fig. 1 is the factor of two decrease in ^{10}Be concentration between 1695, and 1954, and the absence of any other periods of relative invariance. In view of the behavior established by many independent instruments since 1954, it is necessary to question whether there is other evidence for the view that the cosmic ray intensity has varied in the recent past.

Figure 2 presents the earliest known instrumental records of the cosmic radiation, together with ^{10}Be data from Fig1b of Beer et al (1990). H.V.Neher made a long series of high altitude ionization chamber measurements starting in 1933, and extending to 1965. Inter-calibration accuracy was stated to be better than 1% (Neher et al, 1953). A network of five "Carnegie Type C" ground level ionization chambers was established in 1936-7 and was closely monitored and corrected for sensitivity changes (Forbush, 1958). Examination of Fig. 2 shows that there was a 12% decrease in the Neher ionization rate (100g atmospheric depth) between the sunspot minima of 1933 and 1954. The first measurement by the Carnegie network in June 1936 was three years after the 1933 sunspot minimum and after a series of large geomagnetic storms (that modern experience would suggest initiated a globally merged interaction region resulting in a 5% or more downward step in the 11 year modulation seen by a neutron monitor). Nevertheless, the ion chamber average for June 1936 was 5% greater than that for the sunspot minimum value for 1954. Thus these independent sets of instrumental observations, made by two careful workers, both agree that the sunspot minimum intensity decreased substantially between 1933 and 1954. Figure 2 also shows that there is good agreement between these instrumental records and the ^{10}Be data during the interval 1933-1976. Other evidence in support of the variability is obtained from ^{14}C records as will be discussed below. These data therefore all agree that there was a substantial decrease in the cosmic ray intensity prior to 1954. Henceforth, we take the view that the ^{10}Be data in Fig.1 are a valid measurement of the cosmic radiation and its time variation in the vicinity of earth.

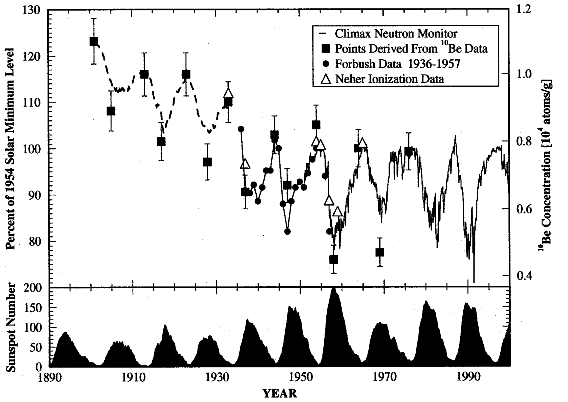

Fig. 2 Cosmic ray data, 1900-2000, together with the international sunspot number. The dotted line 1900-1933 is an estimate of the neutron monitor intensity based upon an 11year variation that is proportional to sunspot number, superimposed on the observed long term variation in the ^{10}Be.

4 The occurrence of ^{10}Be concentrations greater than the ϕ =0 value.

In Fig.1, the ^{10}Be data for the period 1680-1710 are all above the ϕ = 0 MeV line, a situation that is physically impossible in terms of the Gleeson and Axford model. These data are all 5-10 year averages, and the estimates of statistical error made in McCracken (2001) indicate that the measurement error for each of these points is about 2.5%. The observed data exceed the ϕ = 0 value by up to 20%, and therefore this excursions must be regarded as statistically significant. Before proceeding, it is necessary to determine whether this excursion is of terrestrial origin.

As noted above, the ^{10}Be concentration will reflect changes in the efficiency of precipitation of the ^{10}Be, and also the annual snowfall. The period 1645-1715, the Maunder Minimum, occurred at the same time as the "little ice age", and it is likely that stratospheric and tropospheric temperatures were colder, and it is also possible that snow fall was reduced by the lower temperatures in the seas feeding humidity to the polar caps. Both factors might have influenced the observed concentrations of ^{10}Be. This hypothesis can be tested by examining the concurrent ^{14}C record (eg, Beer et al, 1992; Bard et al, 1997), for while the ^{10}Be concentration can be contaminated by the processes outlined above, ^{14}C remains in the gaseous phase, and is immune to such effects. Using mathematical models of the carbon cycle, Beer et al (1992) and Bard et al (1997) have shown that there is close agreement between the ^{14}C and the ^{10}Be variations in the recent past. In particular, the ^{14}C data confirm that the cosmic radiation in the vicinity of 1695 was at the highest value attained in the past 1000 years.

Analysis of the simulations reported by Bard et al (1997) indicates that the ^{14}C data confirms that the anomalous excursion above the $\phi = 0$ line in Fig. 1 was not of meteorological origin.

Long term changes in the geomagnetic field modulate the cosmic ray cut off rigidities, and therefore alter the cosmic ray intensities in the atmosphere. The geomagnetic dipole changed its vector direction quickly in the century prior to 1700AD, however calculations reported here (McCracken, 2001) indicate that this would have resulted in a 0.5% decrease in ^{10}Be precipitation between 1600 and 1700AD, and therefore the 40% increase in Fig 1 cannot be of geomagnetic origin.

The possibility that errors in the Masarik and Beer data has caused the $\phi = 0$ line to be displaced downwards will be discussed in Sect. 6, and shown to be untenable.

5 A long term heliospheric modulation process.

A very unusual feature of Fig.1 is the manner in which the ^{10}Be concentration rises rapidly and at an essentially constant rate throughout the period 1655-1695; that is, throughout the Maunder Minimum. The group sunspot numbers (Hoyt and Schatten, 1998) in Fig. 1 show that the large and rapid increase in ^{10}Be was synchronous with a 50 year period of extremely low solar activity. Note the contrast; (a) the cosmic ray intensity returned to essentially the same asymptotic value (± 3%) for each of the five sunspot minima in the interval 1954-1996, a period of high and strongly variable solar activity, while (b) the cosmic ray intensity increased rapidly by 40% in a monotonic fashion throughout a period when the sun was extremely quiet. Note also that the ^{10}Be concentration exhibits a similar large and prolonged monotonic increase, with essentially identical slope, during the period 1775-1815; that is, the period approaching and during the Dalton Minimum of solar activity.

The instrumental measurements since 1933; the recovery of the 11 year variation in cosmic ray intensity to the same asymptotic value between 1954-1996; the 11 year variations in the ^{10}Be data examined elsewhere (McCracken,2001); and satellite measurements in the far heliosphere (McDonald et al, 2000) all indicate that the physical mechanism that is responsible for the 11 year variation has a relaxation time of ≤ 2 years. The constant sunspot minimum value 1954-1997; and the large quasi linear increase 1655-1695 both suggest that there is another physical mechanism, distinct from that responsible for the 11 year variation, that has a much longer relaxation time. Assume that the cosmic ray intensity $C(t)$ increased during the period 1655-1695 due to the exponential decay of a modulation mechanism described by $C_{1660} + \{C_\infty - C_{1660}\}\{1-exp(-t/\tau)\}$, where C_∞ is the ^{10}Be concentration that would be seen in the absence of any modulation; C_{1660} is the ^{10}Be concentration in 1660; and τ is the relaxation time constant. The lower limit for τ that fits the data in the period 1655-1695 has been determined to be 200 years and the resulting plot of $C(t)$ is superimposed on Fig.1. This fit to the data implies $C_\infty = 2.53 \times 10^4$ atoms/gram. While this result is clearly very speculative, note that this value of C_∞ is 63 % above the highest observed value in 1695, and 97% above the $\phi = 0$ line in Fig.1.

6 Discussion

McCracken (2001) has shown that ^{10}Be data have a mean energy of response of 2.0-2.6 GeV/nucleon. Figure 1 therefore indicates that there is a long term modulation mechanism that has reduced the intensity of cosmic rays at earth in the vicinity of 2 GeV to <50% of the 1695 value. The 11year variation of the 19th Schwabe cycle (1954-65), one of the largest in contemporary records, only had a ^{10}Be amplitude of 21% of the 1695 value. That is, the long term modulation near 2GeV was a factor 2.5 to 3 times greater than the 11year modulation events observed since 1954. The 200year relaxation time indicates that the modulation mechanism is probably in the heliosheath. The fact that the 200 year modulation has been invariant since 1954 means that it has been undetectable using cosmic ray data obtained over the past 50 years. The cosmogenic data such as ^{10}Be, together with satellite measurements in the far heliosphere, are probably the only ways that the heliosheath modulation can be investigated.

The integrating effect of a 200year modulation can explain the long term variations in Fig. 1 in general terms. Thus after 1695, there was steadily increasing solar activity (as measured by the peak sunspot numbers for the individual solar cycles) from 1698 to 1769. Activity then declined to the Dalton Minimum 1810-1820. The ^{10}Be declined rapidly by 50% to 1770; then steadily increased until about 1815. Solar activity then increased and the sunspot minimum ^{10}Be decreased rapidly by 20%. Solar activity then remained relatively high through to the Gleissberg Minimum about 1900. During this period, the decay, and replenishment of the long term modulation by solar activity remained roughly in balance. Solar activity then increased rapidly to 1957, accompanied by a further rapid 25% decrease in ^{10}Be. Thereafter, the replenishment and decay effects remained in balance to the present. Initial inspection indicates that the rate of replenishment of the modulation mechanism appears to be influenced by both the absolute value of peak sunspot number, and its rate of increase from one cycle to the next.

The result that the local interstellar spectrum (LIS) near 2 GeV/nucleon is a factor of >2 times that near earth has implications for calculations of the properties of the LIS itself. Until recently, low energy cosmic ray energy and isotopic spectra were the primary cosmic ray inputs into estimating the LIS, and its source spectrum. Recently, measurements of the 1-20GeV/nucleon spectra using balloon borne spectrometers have imposed another strong restraint, and the result herein provides yet another constraint that will need to be met. Thus the best fit LIS must simultaneously accommodate the factor of >2 at ~2GeV/n prior to modulation, as well as the various measurements made on the modulated spectrum.

The magnitude of the 200year modulation as determined here may have significant impact upon many aspects of cosmic ray studies. The Gleeson and Axford (1968) model that is used in many modulation studies, and in all calculations of the LIS spectrum, may be inappropriate to describe the long term (200 year) modulation. Thus the assumptions of that model are probably violated in the heliosheath. In particular, adiabatic cooling of the cosmic radiation is expected to be less effective there. We have shown that the 200year modulation is a large effect, and this uncertainty therefore could have widespread impact on the study of all cosmic ray data inside the heliosphere.

Sect.4 indicates that the observed ^{10}Be data exceeded the $\phi = 0$ line in Fig. 1 by up to 25% for about 50 years in the vicinity of 1695. The excursion above the $\phi = 0$ line may be due to

(a) The Masarik and Beer calculations of the nucleonic cascades on which the $\phi = 0$ line was based being in error (in addition to uncertainty with respect to the modulation function, as discussed above);

(b) The cosmic ray spectrum outside the heliopaause, the local interstellar spectrum (LIS), being steeper at low energies than that assumed by Masarik and Beer (1999). Then the value of the modulation function, ϕ, required to fit the satellite and balloon data during 1954-97 could be greater than the 440 MeV used in Sect. 2 above, allowing the $\phi = 0$ line to be above the 1695 value in Fig.1.

Examining possibility (a), calculations have shown that 50% underestimates of the ^{10}Be yield functions at energies <4GeV, where the spectral changes are greatest, would only shift the $\phi = 0$ line up by 8%. Extreme changes (>300%) would be required to shift the $\phi = 0$ line up to the peak of the ^{10}Be at 1695AD in Fig. 1, and these appear to be physically unrealistic.

Examining possibility (b), we have attempted to find a steeper LIS that would result in a higher value of ϕ to describe sunspot miminum conditions near 1AU. To date, all attempts have failed badly; particularly to meet the constraints imposed by the 1-20 GeV proton spectra. However, since such fits depend on the use of the Gleeson and Axford modulation potential, it is clear that the uncertainty about its use in the heliopause must be resolved to allow definitive conclusions to be made.

7 Conclusions

This paper has demonstrated that the cosmic radiation observed at earth has been subjected to a large long term modulation mechanism with a relaxation time ≥ 200 years. The observed ^{10}Be data indicate that this modulation mechanism had reduced the ~2 GeV proton intensity by a factor of >2 below the local interstellar spectrum during recent sunspot minima. The ^{10}Be data in the vicinity of 1695 are too high to be explained by the force field modulation function, and there is a speculative argument that suggests that the ^{10}Be concentration could be a further 63% higher in the absence of any solar modulation. The large amplitude of the 200 year modulation means that use of the Gleeson and Axford (1968) modulation theory in its analysis is likely to result in substantial errors. It is proposed that the high values of ^{10}Be in 1695 must be used as a constraining measurement, together with the energy and isotopic spectra observed near earth, in the determination of the properties of the local interstellar comic ray spectrum.

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