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The 2300 year Modulation in the Galactic Cosmic Radiation

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Abstract: This paper examines the properties of the ~2300-year periodicity in the galactic cosmic radiation, previously recognized in power spectra of cosmogenic ^{10}Be and ^{14}C. It shows that the periodicity consists of short episodes (50-100 year) of high cosmic ray intensity, such as accompanied the Spoerer and Maunder Minima, separated by long intervals (>1000 years) of low intensities similar to, or lower than those observed by cosmic ray instruments since 1936. The cosmic ray data are used to investigate the long-term variation in the strength of the heliospheric magnetic field (HMF). The terrestrial and solar implications of the ~2300 yr periodicity are discussed.

The Cosmic Ray Intensity Variations in the Past

The worldwide neutron monitor network has shown that the cosmic ray intensity at sunspot minimum was essentially invariant from 1954-2007, with 11-year modulation cycles depressing the intensity below that level in anti-phase with solar activity. More recently the instrumental ionization chamber measurements (1933-1969), and the cosmogenic ^{10}Be and ^{14}C data have shown that the cosmic ray intensity since 1954 has been one of the lowest in the past 1000 years [1,2,3]. This is illustrated by Figure 1, which shows that the 22-year average "modulation potential" was ~100 MV when the Sun was inactive, increasing to ~650 MV in the present epoch.

Figure 1 shows that there were six periods between 850 and 2000AD during which the cosmic ray intensity was substantially above the adjacent values, and above the intensities observed since 1954. The enhancements near 1700, 1810, and 1895 correspond to the Maunder, Dalton, and the1895 minima evident in the sunspot record. The other three enhancements correspond to the Oort (~ 1050); Wolf (1325-1375); and Spoerer (1420-1540) minima in auroral activity, implying low solar activity. The Spoerer enhancement in

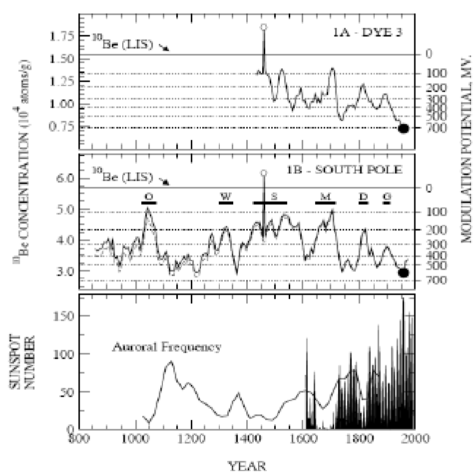

Figure 1: The temporal variation of the cosmogenic ^{10}Be for the interval 850-1958 AD. The periods of low solar activity, and their counterparts in the ^{10}Be records are identified as follows; O=Oort Minimum; W=Wolf; S= Spoerer; M= Maunder; D= Dalton; and G= the Gleissberg Minimum of ~1895. The ^{10}Be concentrations are given in atoms per gram. The right hand scale and the horizontal lines give the modulation potential. The bottom panels present the annual group sunspot number (1600-2000), and the normalized frequency of occurrence of the mid-latitude aurora between 1000-1900 AD. Other details of this figure are given in reference 1.

the cosmic ray intensity appears to have been the most profound- the cosmogenic data indicate that it lasted for about a century, and that the cosmic ray modulation was very low, suggesting a very low level of solar activity. The six minima in solar activity mentioned above are sometimes called the "Grand Minima"

Inspection of Figure 1 shows that the cosmic ray enhancements associated with the Grand Minima had the following characteristics. (a) Their rise and fall times were short, typically ≤50 years. (b) The overall duration is short, typically 50-100 years. (c) The cosmogenic data increased by ~80% above the adjacent values and the modulation potential decreased by ~500 MV to the vicinity of 100-150 MV.

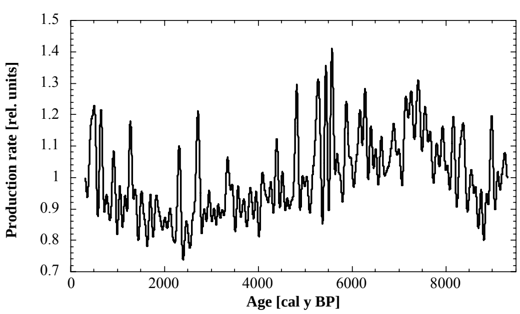

Figure 2: The time dependence of the cosmic radiation derived from the ^{10}Be and ^{14}C cosmogenic data, after passage through a 100 yr low pass filter. The Y axis gives the production rate as a ratio with respect to the average for the whole interval. The time is given in the "Before Present" time scale (BP) that gives the year prior to 1950. Note that the most recent data are at the left of the figure. The three enhancement events at the left are the Spoerer, Wolf and Oort Minima given in Figure 1.

Figure 2 presents the variation in the cosmic radiation at Earth over the past 9500 years. The quantity plotted is the first principal component of the ^{10}Be and ^{14}C data, as described by Beer and McCracken elsewhere in this conference [4]. This form of presentation extracts the cosmic ray variation that is present in both cosmogenic archives, while eliminating the variations due to atmospheric and other non-production effects. Being based on two completely independent forms of cosmogenic data, we believe that it gives the best estimate of the changing cosmic ray intensity over the past millennia. The 1150 years on the left hand side of Figure 2 is the period presented in Figure 1. Note that the data in Figure 2 do not include the interval 1600-2000 AD, and therefore do not show the enhancements associated with the Maunder, Dalton, and the Gleissberg Minimum of 1895 that are included in Figure 1. The enhancements associated with the Spoerer, Wolf and Oort Grand Minima, however, are clearly evident in Figure 2. It is clear from Figure 2 that there was a substantial number of enhancement events prior to 1000 BP that exhibit characteristics similar to the Spoerer and other enhancement events shown in Figure 1.

Archeomagnetic measurements show that the geomagnetic dipole has changed substantially over the past 9500 years, being ~40% stronger than the present value in the interval 1000-3000 BP, and ~ 30% weaker prior to 4500 BP [5]. As a consequence, the geomagnetic cut-off rigidity has changed over time, worldwide, resulting in a ± 10% modulation of the production rates of the cosmogenic nuclides [6]. The time dependent upper and lower envelopes of the curve in Figure 2 are the consequence of these secular changes in the geomagnetic cutoff rigidity.

Examination of Figure 2 shows that there were ~24 enhancement events in the past 9500 years, with amplitudes and durations similar to the Spoerer, Wolf and Oort minima evident on the left hand side of the Figure. Clearly, the enhancement events were not randomly distributed in time. As Figure 1 shows, there were five enhancement events between 1050 and 1800 AD (150-900 BP). In the following we refer to this as the "Spoerer episode". By way of contrast, there were no enhancement events at all in the 2000 year period 2700-4700BP. There was, however, an episode of four enhancements in the vicinity of 5500 BP that was quite similar to the "Spoerer episode". Thus the separations of the enhancements within the episode (~200 yr), and the overall duration of the episode (~800 yr) were similar, as were the amplitudes of the individual enhancements. There was another prolonged episode in the vicinity of 7500 BP.
In summary, the periods of increased cosmic ray intensity similar to those that accompanied the

Maunder and Spoerer minima in solar activity only occurred for about 25% of the past 9,500 yr.

The ~2300 yr Periodicity

It has long been known that the power spectra of the both the ^{10}Be and ^{14}C cosmogenic data show a component with a periodicity of ~ 2300 yr [e.g. 7], however little is known about its origin, or correlation with other solar phenomena. Figure 2 removes much of the mystery. The figure shows that the clusters of enhancements such as the "Spoerer episode" at ~450 BP, ~5,500 BP, ~8,000 BP, together with the pair of enhancement events centered on 2,500 BP represent periods of high average values of the ^{10}Be and ^{14}C data, that the power spectra algorithm will recognize as an approximate periodicity of (8000-450)/3=2500 yr. Furthermore, the figure indicates that the most recent maxima of this ~2500 yr periodicity occurred in the vicinity of the Spoerer or Maunder minimum (i.e., centered on ~ 1500 AD, or 450 BP). By analogy with the correlations evident in Figure 1, we conclude that the maxima of the ~2500 yr periodicity detected in the power spectra correspond to the periods of alternating low and high solar activity (i.e., the Spoerer episodes). The minima of the ~2500 yr periodicity would be similar to the period 2700-4700 BP, which had no enhancement events, and which we interpret in terms of the Sun remaining in an active state with the average modulation potential ≥ 700 MV.

Figure 3 provides further insight into the manner in which the cosmic ray modulation has varied over time. Here, in concept, a numerical filter tuned to frequency f, say, has scanned the full 9500 yrs of the ^{14}C data in 1000 year blocks at a time, and determined the amplitude of the signals at that frequency in each block. This has then been repeated for all periodicities in the range 100<T<1000 yrs. Combining the results, the figure shows how the frequency content of the ^{14}C data has varied with time.

Figure 3 shows that there are three persistent periodicities in the modulation process. All three have their greatest amplitudes coincident with the "Spoerer episodes". The three periodicities are as follows. (a) A persistent periodicity in the vicinity of 150 yr. (b) In the vicinity of ~210 yrs. This has been long recognized in the ^{14}C data, and called the Suess (or de Vries) periodicity. The figure shows that this is persistent, and generally of higher amplitude than the 150 yr periodicity. (c) In the range 350-550 years. In addition, there is the ~2500 yr periodicity discussed previously.

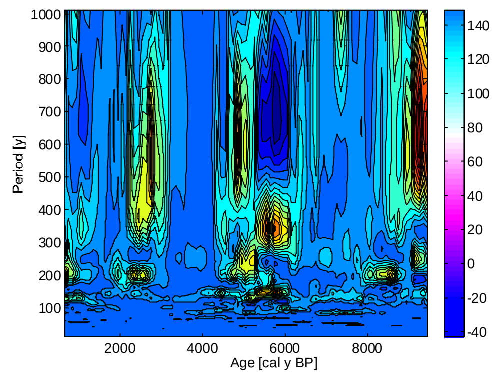

Figure 3: The manner in which the frequency components of the ^{14}C production rate has varied over the past 9,500 yr. The Y axis gives the period of the components. The Z axis (colour) gives the amplitude of the components. Note that the high component amplitudes correspond to the multiple enhancement episodes at ~2,500, ~5,500, and ~ 8,000 BP in Figure 2.

Discussion

McCracken [8] has used the ^{10}Be data for the past 500 years to infer that the 11 year average strength of the heliomagnetic field (HMF) near Earth was ~1 nT during the Spoerer Minimum, and trending up thereafter to an average value of ~7 nT since 1954. A similar result was obtained by Solanki et al [9] based upon the sunspot record since 1610 AD. By analogy, we propose that the peaks of the 24 enhancement events in Figure 2 correspond to values of the HMF of ~1 nT, while the persistently low cosmic ray intensities between these events correspond to HMF strengths of ≥ 7nT. We note that the relative amplitudes of the enhancement events circa 2500, and 5500 BP are greater than that of the Spoerer minimum (450 BP), and speculate that this implies that the HMF strength was greater than 7 nT in the vicinity of those dates.
It is clear from the above that there have been large secular changes in the cosmic ray intensity,

and HMF strength, over the past 9500 yr. The strength of the HMF affects the nature of the interaction of the solar wind with the Earth's magnetosphere, and as a consequence there may have been long term changes in the nature of geomagnetic activity. The irradiance of the Sun changes throughout the 11 year solar magnetic cycle, and it is possible that it will have varied throughout the ~2300 yr periodicity in a similar manner. This could result in changes in terrestrial climate, with the peaks of the 24 enhancement events in Figure 2 corresponding to lower irradiance (cooler terrestrial climate) and the low intensities corresponding to higher irradiance (warmer climate).

The changes in the cosmic ray intensity are due (in large part) to the varying strength of the HMF. This is, in turn, controlled by the strength of the solar magnetic fields. From Figure 3, we speculate that the solar magnetic fields vary with quasi-periodicities of ~150, ~210, ~350 to 600, and ~2300 yrs. (and shorter periodicities of ~80 and 22 years not investigated here). We speculate that these frequencies are determined by the nature of the solar dynamo that controls the sunspot and other solar magnetic fields. The strength of the solar magnetic fields may strongly affect the acceleration of cosmic rays by the Sun, and consequently the occurrence of solar energetic particle events is expected to exhibit the periodicities evident in Figure 3.

Acknowledgments

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