Properties of the Long Term Heliospheric Modulation - Tests to be Met by Modulation Theory

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Abstract

The long term heliospheric modulation of the GCR, 850-1980 AD, exhibits features that are proposed as tests of the contemporary theories of cosmic ray modulation, and the evolution of the interplanetary magnetic field. They include *(1)* strong modulation during the Maunder Minimum; *(2)* a precipitous ∼50% decrease of the GCR in the vicinity of 2 GeV/nucleon between 1700 and 1725; and *(3)* a 5 year variability at times of low solar activity.

1. Introduction

Correlated century scale variations in the cosmogenic ^{10}Be sequestered in polar ice, and in ^{14}C in biological materials, demonstrate that there are long term changes in the GCR incident on Earth [1,2]. They have been shown to be associated with long term changes in solar activity; in particular, the intensity of the GCR was substantially higher at Earth during the Maunder and Dalton minima (*circa* 1645-1715, and 1810-30, respectively). This paper examines variations in the ^{10}Be in the interval 850-1980 AD that provide insight into features of the GCR modulation process that have not been evident since the commencement of the instrumental record in 1933.

2. Method

Figure 1 displays the ^{10}Be data from Dye 3, Greenland, and the South Pole [1]. This paper is concerned with the long term (>11year) variations in the GCR, and therefore the Dye 3 data are 11 year averages and the South Pole data are 21-24 year averages in order to reduce the scatter in the data due to the 11 year variation in the GCR [7]. The average values for the extended interval of high ^{10}Be values, 1460-1680, were used to normalize the two sets of data.

Atmospheric and geomagnetic effects introduce variations into the ^{10}Be record, and for this reason we use a "two data source" method to verify the effects discussed herein. The longer term (50 year) variations in Figure 1 have been shown to be present in the ^{14}C record, and since ^{14}C is not sensitive to

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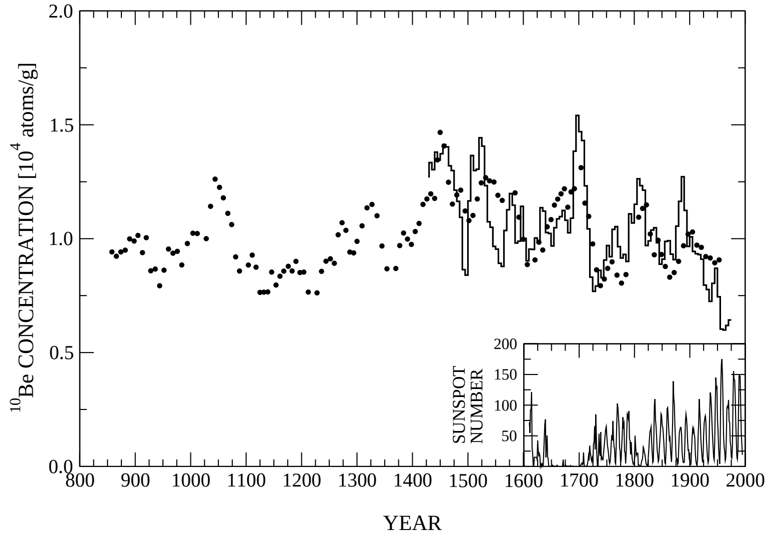

Fig. 1. The 11 year average ^{10}Be data from Dye 3, Greenland (histogram) and 21-24 year averages (dots) from South Pole [1].

variations in atmospheric mixing, this eliminates climate change as a source of the longer term variations [1,2]. For shorter time scales, variations in regional meteorology, such as variable snow fall, affect the concentration of ^{10}Be. It is unlikely that they will be correlated in the two polar caps, and we assume that large variations that are seen in both are due to changes in the GCR intensity. Figure 1 shows a good agreement between the two records in the overlapping interval 1430-1950, despite the 21-24 year averaging of the South Pole data that attenuates some short scale changes evident in the 11 year data from Greenland.

3. Results and Discussion

The limits of the modulation process. Figure 1 shows that the 11-22 year averages of the ^{10}Be data have varied by a factor of ~2.5 throughout the past 1150 years. The data appears to reach an asymptotic limit in the vicinity of 1450, 1550, and 1700. These maxima, and high values in 1820 and 1890, all appear to be associated with low solar activity. The figure shows that the GCR intensity returned repeatedly to low values that are similar (but somewhat above) those of the present epoch The maximum of the ^{10}Be response function lies in the range 0.8-1.8 GeV/nucleon [7], and the above shows that the modulation process has resulted in a ~2.5 variation in the intensity of the ~2 GeV/nucleon GCR over the past 1150 years.

Modulation during the Maunder Minimum. The GCR exhibited substantial modulation during the Maunder minimum [3]. To study this further, the upper graphs in Figure 2 display the ^{10}Be data from Dye 3, applying a weighted average to the annual data with weights 1, 2, and 1. There are large, rapid changes in both intervals, the ^{10}Be data varying by ±30% between 0.7 and 1.3x10^4 atoms/g in each case. The modulation of the GCR requires the presence of magnetic fields, and Figure 2 indicates that the strength and properties of the heliomagnetic field were similar during both periods. The lower panels in Figure 2 show the group sunspot number [4], N_G; note the logarithmic scale for $N_G<10$. Comparing the panels, note that while the amplitudes of the variations in ^{10}Be were similar during the two periods, N_G differed by a factor of about 50. Since 1950, the GCR intensity has shown an approximately linear regression with N_G, however Figure 2 shows that this regression relationship did not pertain during the Maunder minimum.

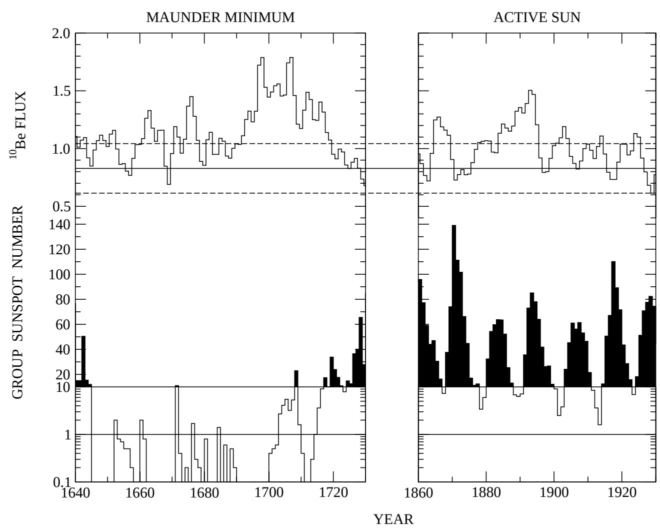

Fig. 2. Comparison of the ^{10}Be data, and the sunspot numbers *(a)* during the Maunder Minimum, and *(b)* during a period of high solar activity.

Modulation during the interval 1700-1725. Figure 1 shows that in 1700 the ^{10}Be concentration at Dye 3 was one of the highest values reached in the period 1423-1980. Over the subsequent 25 years it declined rapidly to the lowest value attained prior to 1933 (see also Figure 2). The 21-24 year average data from the South Pole in Figure 1 exhibits this rapid decrease, as does the cosmogenic ^{14}C [5]. Taken together, these three data sources confirm that there was a precipitous ∼50% decrease in the ∼2 GeV GCR in the 25 years, 1700-1725. The Maunder minimum ended in 1715, and Figure 2 shows that the sunspot number remained relatively low until 1725, yet by then the GCR modulation had changed from a very low value near 1700, to one of the highest values attained in 1150 years. Sunspot activity continued to rise until late in the 18th century, yet the ^{10}Be data shows that the GCR rose after 1725.

Implications regarding the cosmic ray modulation process. From the above, it is clear that there were times in the past when the modulation of the GCR near 2 GeV was poorly correlated with the sunspot number. Further, we have recently reported that the GCR exhibits a 5 year variation at times of low solar activity [8]; one such episode is evident in the interval 1698-1718 in Figure 2. The characteristics of the cosmic ray modulation are determined by *(a)* the scattering properties of the interplanetary magnetic field, as influenced by turbulence in the solar wind; *(b)* drift motions in the heliospheric current sheet; and *(c)* the amount of modulation in the heliosheath [6]. All three may change substantially at a time of low solar activity. For example, it is possible that the precipitous drop in GCR intensity from 1700 to 1725 was due to a combination of an increase in scattering properties, and a rapid increase in the modulation in the heliosheath as solar activity increased. It is proposed that the three observations: *(1)* the strong modulation during the Maunder minimum; *(2)* the precipitous ~50% decrease in GCR 1700-1725; and *(3)* the occurrence of the 5 year variation at times of low solar activity, constitute an important test for the theories and parameters of the GCR modulation process. They will also allow the theories of the development of the solar and interplanetary magnetic fields to be tested.

4. Conclusions

It is concluded that *(1)* the 11 and 22 year average GCR intensity near 2 GeV/nucleon has varied by a factor of ~2.5 over the past 1150 years, and that it has been at its lowest value since ~1965; *(2)* there was strong modulation of the GCR during the Maunder minimum, implying substantial interplanetary magnetic fields; *(3)* at a time of only mild solar activity (1700-1725), there was a precipitous ~50% decrease in the GCR intensity that indicates that the modulation process developed to a strength that was not achieved again until 225 years later. These properties, together with the 5 year variation, are proposed as a "test" for any model of the cosmic ray modulation, and the development of the heliospheric magnetic fields as a function of time.

5. References

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