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Long Term Changes in the Residual Modulation of the Galactic Cosmic Radiation

K.G.MCCRACKEN[1]
[1]*University of Maryland*
jellore@hinet.net.au

Abstract: The residual modulation refers to the invariant level of modulation (modulation potential approximately 450 MV) observed at sunspot minimum since the commencement of the neutron monitor record in 1951. Satellite measurements of the heliomagnetic field show that it exhibited a similar invariance (~5.2 nT) between the sunspot minima of 1965 and 1996. The cosmic ray record since 1428 shows that the residual modulation has increased steadily since the Spoerer solar minimum in the 15th century. Three independent reconstructions of the heliomagnetic field (HMF) (two since the middle ages) show that it also exhibited step-like changes. The relative importance of diffusion-convection processes, and drift processes are discussed as a function of the strength of the HMF. It is proposed that the drift processes are more pronounced at times of low HMF strength, explaining the more pronounced 22-year variation of the galactic cosmic radiation at earlier times, compared to during the neutron monitor epoch. The paper concludes with speculation that the solar magnetic fields exhibit an ~2300 year periodicity, and that solar activity modulates that field at the frequencies of 11, 22, ~80, ~230 years, leading to the intensity variations observed in the cosmogenic records.

Introduction

Recent studies have shown that the present day intensity of the galactic cosmic radiation (GCR) is substantially lower than in previous centuries [1,2]. These studies show that the sunspot minimum intensities since 1954 can be characterized by a modulation potential (φ) of ~450 MV, compared to φ < 100MV during the Spoerer (1420-1540) and Maunder (1645-1715) Grand Minima. By combining the instrumental records since 1933, and the cosmogenic ^{10}Be data prior to that date, McCracken and Beer [3] have developed the "pseudo-Climax" neutron monitor record for the interval 1428-2005 shown in Figure 1. In the absence of any modulation (φ =0 MV), the local interstellar spectrum (LIS) of the GCR would be incident on Earth, resulting in a pseudo-Climax counting rate of 119.5% with respect to the observed value for August, 1954.

The Residual Modulation

The term "residual modulation" refers to the manner in which the cosmic ray intensity remains depressed below the LIS value between successive solar cycles. This is most clearly illustrated by the period 1954- 2005 in Figure 2 where the Climax counting rate consistently recovers to an approximate asymptote of ~100% after each of six solar cycles [3], well below the LIS value of 119.5%. That is, there was persistent modulation of the GCR in the absence of significant solar activity.

Contemporary satellite measurements show that the strength of the heliospheric magnetic field (HMF) has exhibited an approximate asymptotic of 5.2nT since 1965. The substantial amount of "residual modulation" during these sunspot minima is consistent with these values of HMF, the observed solar wind speed, and the cosmic ray transport equation of Parker [4].

Examination of Figures 1 and 2 shows that the pseudo-Climax counting rate at sunspot minimum decreased by ~18% between 1900 and 1954. That is, the residual modulation at sunspot minimum increased steadily from ~150 MV circa 1900, to ~450 MV in 1954. The figures show that this monotonic increase in the residual modulated correlated with a steady increase in the peak values of the sunspot numbers for the solar cycles from 1900 to 1954.

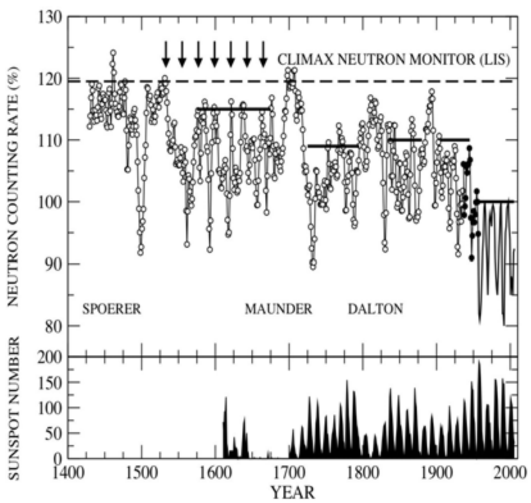

Figure 1: The observed (1951-2005) and estimated (1428-1954) Climax neutron data . The dotted line is the estimated rate in the absence of solar modulation. The arrows are at 22 year intervals. From [3].

Figure 2 shows that residual modulation has been a persistent feature of the GCR intensity at Earth over the past five centuries. Thus the counting rate was depressed by ~10% (compared to the adjacent "Grand Minima") during the active phases of the Gleissberg cycles 1730-1790, and 1830-1880. The maximum counting rates during the interval 1575-1675 were ~5% below the LIS value, this being the interval between the Spoerer and Maunder Grand Minima.

The heavy lines in Figure 2 are estimates of the residual modulation during the four intervals associated with the Gleissberg periods of enhanced solar activity since 1428 AD. These estimates demonstrate that the amount of residual modulation increased substantially (i.e., the intensity decreased) between the Gleissberg maximum of 1540-1644 and the two subsequent maxima; and that it increased further between the sunspot minima of 1944 and 1954. This implies that there was a systematic change in the heliospheric environment at sunspot minimum over the past 580 years. It is fortuitous that we have extensive satellite and terrestrial measurements of the "residual modulation" episode of 1954-2007, and this allows us to interpret the nature of the earlier episodes of residual modulation.

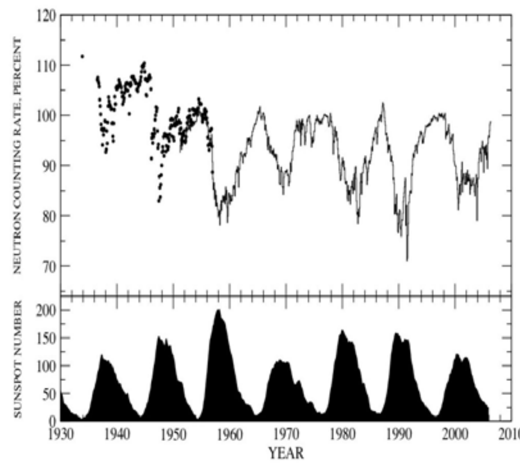

Figure 2: The observed neutron data, 1951-2007, and the estimated annual counting rates based on ground level and balloon borne ionization chambers. From [3].

The Heliomagnetic Field

Figure 3 presents the estimates of the strength of the heliomagnetic field (HMF) near Earth [5], based on an adaptation of the inversion methodology of Caballero- Lopez et al [6]. Figure 4 plots the 11-year running averages of the estimates made by Lockwood et al [7] , Svalgaard and Cliver [8], and Solanki et al [9]. The first two are based on the manner in which the magnetic pressure in the solar wind introduces short term variations into the geomagnetic record. The third employs a forward model of the magneto-hydrodynamic transport of magnetic fields from the Sun's active regions, based on the historic sunspot record 1700-2000. The fourth curve displays the 11-year running averages of the estimates in Figure 3 based on the pseudo-Climax neutron monitor record. The relatively good agreement between curves 1, 3 and 4 provides confidence in the overall validity of these three independent methods. Accordingly, the estimates of the HMF in Figure 3 will now be used to discuss the long term trends in the HMF.

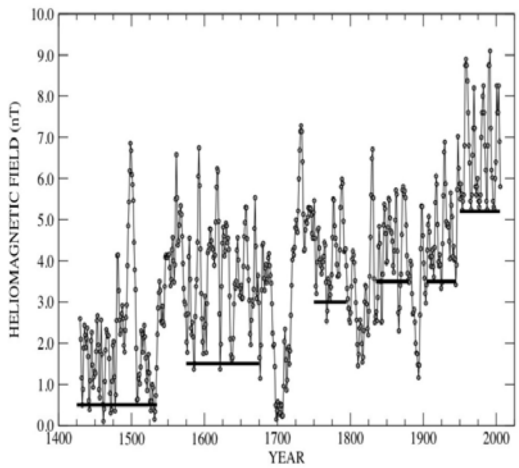

Figure 3: The estimated heliomagnetic field, 1428-2005, based on the data in Figure1. The data are annual estimates, passed through a 1.4,6,4,1 binomial filter.

The most striking feature of Figure 3 is the steady long-term change in the estimated strength of the HMF between the 15th and the 21st centuries. As discussed above, the HMF at sunspot minimum exhibited a "floor" of ~5.2 nT throughout the interval 1954-2005. Examination of Figure 3 shows that there have been similar "floors" in the past, indicated by the thick horizontal lines. For the 120 year duration of the Spoerer Minimum, the minimum HMF was ~0.5 nT. With the resumption of solar activity after the Spoerer Minimum, the HMF floor was ~1.5 nT, with the field increases above that level exhibiting 11-year and 22-year periodicities. The minimum field strength then returned to ~0.5 nT during the Maunder Minimum. Between the Maunder and the Dalton Minima the heliomagnetic floor was ~3.0 nT, and ~3.5 nT between the Dalton Minimum and the Gleissberg Minimum of 1889-1901. It then returned to ~3.5 nT at the sunspot minimum of 1911, and then increased to the modern level of ~5.2 nT between 1944 and 1954. Clearly, these several floor values of the HMF correspond to the several episodes of residual modulation in Figure 1.

Discussion

Figure 1 shows an apparent tendency for the cosmic ray modulation to assume a 22-year character at times of low overall modulation. This can be seen in the interval 1580-1700, and in the vicinity of ~1755, and 1870-1890. Caballero-Lopez et al [6] have computed the modulation as a function of the polarity of the heliomagnetic field and their Figure 5 shows that the qA>0 modulation becomes progressively weaker compared to qA<0 as the overall depth of modulation decreases. (A is the signed magnitude of the solar magnetic field, and exhibits a 22-year periodicity). That is, the cosmic ray record, and the calculations based on the cosmic ray transport equation shows that the 22-year component of the cosmic ray modulation becomes more dominant during periods of low solar activity. This has been reported previously for the Maunder Minimum by Beer et al [10] and Usoskin et al [11].

The power spectra studies of the cosmogenic data show that there is an ~ 2500 yr periodicity in the cosmic radiation at Earth [12], the most recent maximum being in the vicinity of the Spoerer minimum (1420-1540). Elsewhere [3], McCracken and Beer have speculated that the steadily decreasing cosmic ray intensity evident in Figure 1 may be portion of that periodicity. In [13] at this conference, they have shown that the ~2500 yr periodicity is primarily due to the occurrence of several enhancement events, such as occurred during the Spoerer and Maunder Minima, every ~2500 yr. It remains to determine whether the strength of the residual modulation evident in Figure 1 for the current epoch (1954-2007) has been exceeded in the past. The cosmogenic data will allow this to be studied in the future. Those data should also allow us to determine whether the strength of the "floors" in the HMF (e.g., Figure 3) was greater than the present day value of 5.2nT at earlier times.

Acknowledgements

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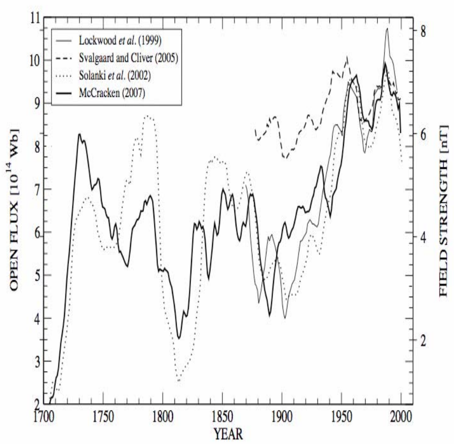

Figure 4: The 11-year running averages of the heliomagnetic field estimated using three different methodologies, as outlined in the text. Curves 1 and 3 are estimates of the total magnetic flux from the Sun. Curves 2 and 4 are estimates of the heliomagnetic field strength near Earth.

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