Neutron Monitor Observations of the 2009 Solar Minimum

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Abstract. The solar minimum period in 2008 and 2009 is characterized by a prolonged cosmic-ray maximum intensity. In the so-called qA<0 magnetic cycle, one rather expects a sharply peaked profile, as occurred during the solar minimum periods 22 and 44 years ago. The observations of the Sanae, Hermanus, Potchefstroom, and Tsumeb neutron monitors are used to investigate this behaviour in terms of propagation conditions due to solar activity, the heliospheric magnetic field, and the profile of the wavy current sheet in the field. We conclude that, although solar activity parameters are quite different from previous solar minima, the control of these parameters over the cosmic-ray modulation is still according to the current paradigm.

Keywords: solar cycle, neutron monitors, heliospheric modulation

I. INTRODUCTION

Neutron monitors (NM) have observed the cosmic-ray intensity since 1951, when the Climax NM was commissioned. Since then, over 100 of these instruments have recorded the cosmic-ray intensity at one time or another. Currently, there are approximately 40 operating NMs in the world-wide network. They provide a long-term, stable baseline for modulation studies. Details of this network were summarised in [7].

We operate four of these NMs, at Sanae in Antarctica, at Hermanus and Potchefstroom in South Africa, and at Tsumeb in Namibia. Their combined data set is shown in Figure 1. The fifth set is that of the Sanae neutron moderated detector (NMD), which consists of a standard NM64 configuration, but without a lead producer. This leads to a yield function that admits more lower energy particles than the standard NM, as described in [9].

The Hermanus NM has operated continuously since 1957, covering more than four 11-year solar modulation cycles, and more than two 22-year solar magnetic cycles. The other NMs were established later. The data gap in 1995 and 1996 on the Sanae NMs is due to the move and reconstruction of the South African base from the ice shelf around the continent to a solid rock outcrop called Vesleskarvet.

II. GENERAL FEATURES OF THE LONG-TERM MODULATION

Figure 1 presents a long-term comprehensive overview of the cosmic-ray modulation over the past 50 years. The cutoff rigidity dependence of the modulation is such that the modulation amplitude at Tsumeb, at cutoff rigidity 8.1 GV, is ≈15%, while for the Sanae

NMD at 0.8 GV it is twice as large at ≈30%. The now well-established alternating peak-plateau nature of subsequent cosmic-ray maxima shows on all the stations: in May 1965 and in March 1987 the intensities reached well-defined peak values, while during the periods 1974-1977 and 1996-1997 there were much flatter, less sharply defined cosmic-ray maxima. This behaviour is understood in terms of drift of cosmic rays in the heliospheric magnetic field, as described for instance by [4]: in 11-year periods such as from ∼ 1960 to 1970, ∼ 1980 to 1990, and ∼ 2000 to present, the solar and heliospheric magnetic fields in the northern hemisphere generally point towards the sun, and away in the southern hemisphere. In the in-between periods from ∼ 1970 to 1980, and ∼ 1990 to 2000, the field directions are reversed. Positively charged particles experience gradient and curvature drift in such a field that it is directed from pole to ecliptic and outward along the neutral sheet separating the hemisphere during the former so-called qA<0 periods, and oppositely during the latter qA>0 ones.

This comprehensive data set shows that the peak/plateau intensity ratios have a different rigidity dependence than the overall modulation cycle. For instance, the plateau intensity at Tsumeb in August 1997 is 2.8% below the peak intensity of March 1987, with the corresponding numbers for the other four stations being 3.3% at Potchefstroom, 2.6% at Hermanus, 3.0% at Sanae, and 2.4% for the Sanae NMD. These five ratios are of the same order of magnitude. Thus the peak/plateau ratio is essentially independent of cutoff rigidity. On the other hand, the modulation amplitude for the Sanae NMD is twice as large as at Tsumeb (30% vs. 15%). Thus there is a definite difference in the rigidity dependence of the modulation during qA>0 and qA<0 cycles. This can be understood in terms of the opposite drift patterns during these epochs. We also note that at lower energies, e.g. for 150 to 380 MeV/n (1.1 to 1.8 GV) He, measured on IMP8 and ACE by McDonald [5], the plateau intensities are higher than the peak intensities. This rigidity dependent difference in the peak/plateau ratios led Moraal et al. [6], [7] and Reinecke et al. [8] to suggest that the modulated spectra at NM energies in opposite magnetic cycles should contain more than one crossover. The current data set thus confirms this earlier inference.

III. FEATURES OF THE CURRENT SOLAR MINIMUM

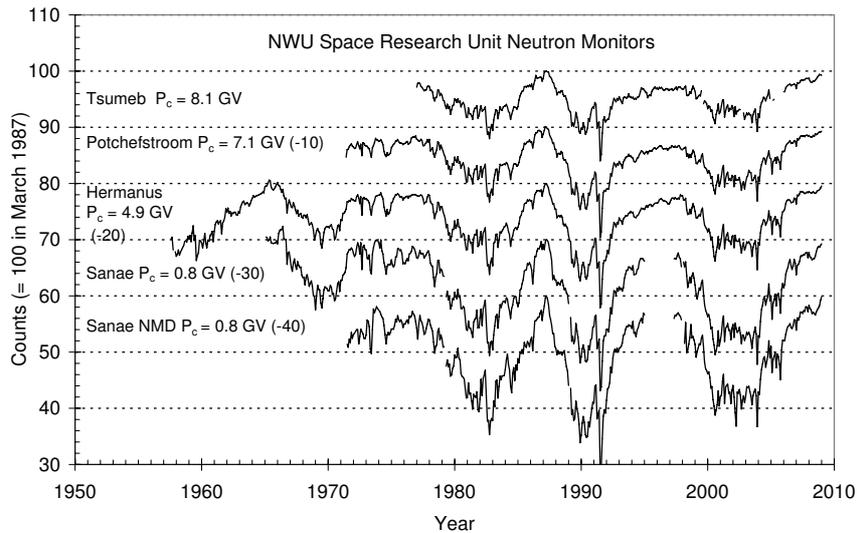Next we focus on the current solar minimum period, from about 2006 onwards, because solar activity during

Fig. 1: Monthly average counting rates of four NMs and a neutron moderated detector (NMD), normalised to 100 in March 1987.

this period differs significantly from that in previous solar minima. We note from Figure 1 that during this current minimum the intensities at all five stations have recovered to very nearly the 100% level, which is the normalisation level used for March 1987, and which also was the level for Hermanus in May 1965. Hence, there is no detectable difference with previous solar minima. It should be noted that there is no consensus about this - the web pages with unpublished data of a few neutron monitors indicate that their 2009 level has already climbed more than 1% above the 1987 level. Such differences justify the importance of our neutron monitor calibration project, described in [3] and references therein.

The rate of recovery is visibly different than during the recoveries of one and two solar magnetic cycles ago, approaching the maximum in a more exponential fashion than from 1984 to 1987 and 1962 to 1965. The current double (22-year) modulation cycle may also become considerably longer than the previous two: the maxima of May 1965 and March 1987 occurred 21 years and 10 months apart, while from March 1987 to May 2009 (when the intensities had not yet peaked) already covers a period of 22 years and 2 months.

These differences in the modulation as compared to previous minima are much smaller than the differences in modulating agents between these cycles. Figure 2 is a combined plot of nine month running averages of the Zurich sunspot number, the heliospheric magnetic field, and the tilt angle (classical value) between the heliographic and heliomagnetic axis that produces the wavy nature of the neutral sheet between oppositely pointing HMF directions. These three parameters are generally recognised as indicators of overall modulation strength. The sunspot number is a proxy for the amount of turbulence in the HMF, which determines

the magnitude of the cosmic-ray diffusion coefficients parallel and perpendicular to the mean field. Likewise, it is generally perceived that the magnitude of these diffusion coefficients is inversely related to the strength of the HMF. Finally, it was noted above that the waviness of the neutral sheet is a strong modulation agent during $qA < 0$ cycles, especially near solar minimum.

There are large differences in the solar cycle dependence

TABLE I: Length of solar cycles in sunspot number, HMF strength and HMF tilt angle

cycle	SS length yy mm	HMF length yy mm	Tilt length yy mm
20	11 10	–	–
21	11 00	9 03	10 08
22	9 02	10 03	9 05
23	>12 08	>13 00	>12 10

of these three parameters, as well as large differences from one solar cycle to the next. These will not be addressed here. It is significant, however, that during the three solar minima separating cycles 20, 21, 22 and 23, each of these three parameters receded back to approximately the same value, i.e. a sunspot number to ≈ 10, the HMF at Earth to 5.5 nT, and the tilt angle to $\approx 5°$. However, the box at the right-hand side of the figure draws attention to the fact that conditions are much different during the current minimum. The sunspot number is receding back to smaller values than before, the HMF drops off to ≈ 4.2 instead of 5.5 nT, while the tilt angle remains significantly higher, at $\approx 12°$, instead of the usual $\approx 5°$. Furthermore, Table 1 shows that for all three these parameters the current incomplete cycle (23) is significantly longer than any of the previous three.

Figure 3 shows how the Hermanus NM counting rate responds to variations in these three parameters. The top panel compares this counting rate with sunspot number,
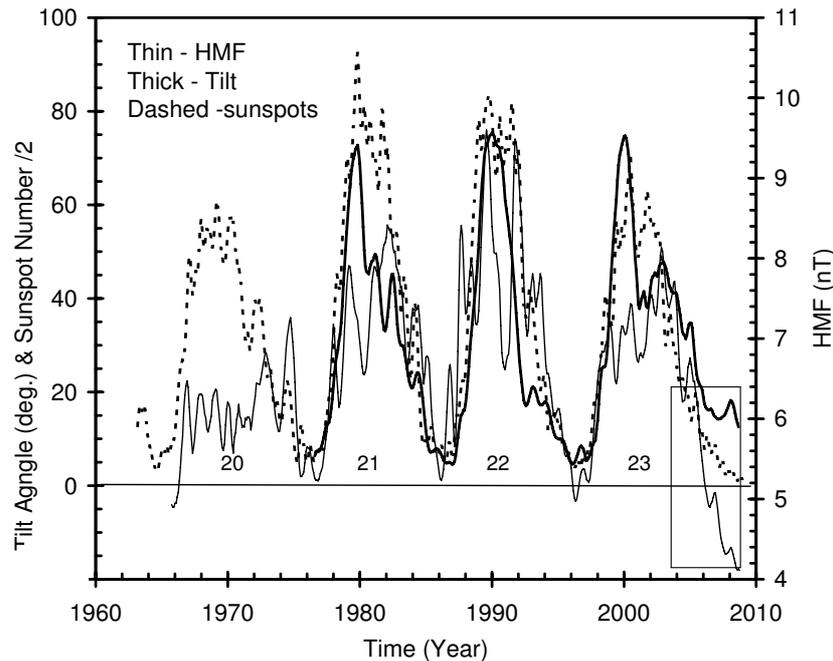
Fig. 2: Nine-month running averages (weights 1,2,3,4,5,4,3,2,1) of the Zurich sunspot number (divided by 2) (http://solarscience.msfc.nasa.gov /greenwch/spot-num.txt), the HMF strength near Earth (http://omniweb.gsfc.nasa.gov/cgi/nx1.cgi), and the tilt angle of the wavy neutral sheet (http://wso.stanford.edu/Tilts.html). The box at the bottom right emphasizes the large differences with respect to previous solar minima.

the middle one with HMF tilt angle, and the bottom one with HMF strength. To aid visual comparison, the quantities are linearly scaled as noted on the figure, to give them equal amplitude in the ascending phase of solar cycle 22 (from 1987 to 1990).

The top diagram shows that the NM counting rate generally lags behind the sunspot number, which is as expected, because solar activity levels have to be communicated throughout the heliosphere before the cosmic-ray intensity will respond to them. However, the amount of lag varies significantly, being very small for 1987 to 1991 for instance, and the quality of correlation therefore varies. This leads to the well-known fact that solar activity is a poor predictor of modulation.

The middle and lower panels show, however, that the correlations with tilt angle is not better, and that with HMF strength is even worse: the short-term variations in the HMF are much larger than those of the other two parameters (as well as those of the cosmic rays), while from 1966 to 1971 there is almost no long-term field variation at all. In later years there are several periods in which the cosmic-ray intensity actually leads the variations in the field.

These complex correlations and their deviations demonstrate that the modulation is simultaneously controlled by several parameters.

IV. MODULATION CALCULATION

Finally, we ask whether the current level of modulation, which is similar to the levels of March 1987 and May 1965 (Figure 1), can be understood quantitatively, in view of the large differences in HMF strength and tilt angle when compared to these previous two solar minimum periods (Figure 2).

For this purpose we solved the cosmic-ray transport equation numerically with a set of parameters as described in detail by Caballero-Lopez et al. in [1]. The parameters of those solutions provide the best available fit to observations right throughout the heliosphere, which was assumed to have a boundary at 120 AU, and a termination shock of the solar wind at 90 AU. Specifically, Figure 6 of that paper fits the intensities during solar minimum periods in the qA$<$0 solar magnetic cycle. We used the same parameters as for that figure, but instead of keeping the HMF fixed at 5 nT (at Earth), and the neutral sheet tilt angle at 10°, we calculated the amount of modulation as function of these two parameters.

The results are shown in Figure 4, which gives the modulated intensity at Earth relative to the interstellar intensity at a rigidity of 3 GV, which is representative of NM energies. The full line shows the intensity variation with tilt angle for a fixed value of the HMF. This represents the well-known behaviour that in a qA$<$0 cycle the intensity near the ecliptic plane is a maximum, decreasing towards the poles, and that this maximum is strongest defined when the waviness of the neutral sheet is small. The dashed line shows the response to the strength of the HMF (for fixed tilt angle), assuming
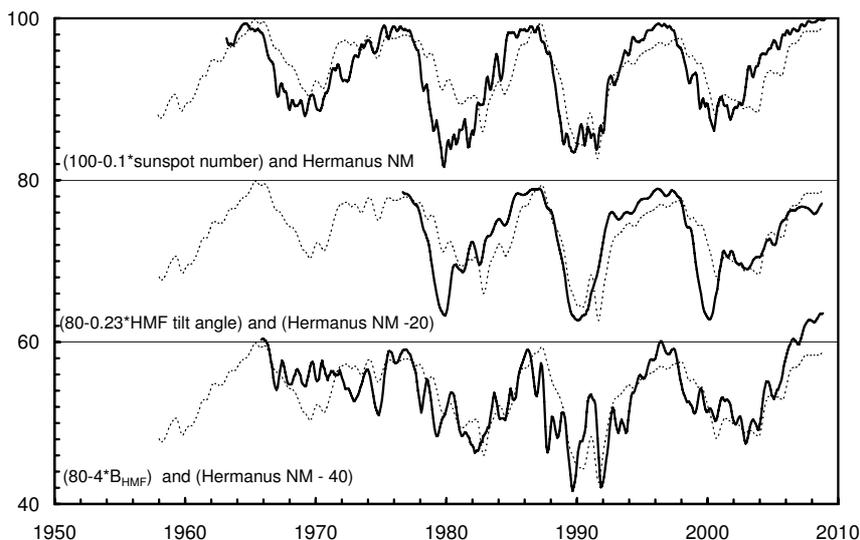
Fig. 3: Hermanus NM counting rate (dashed lines) compared with scaled values of the sunspot number (top), heliospheric magnetic field (middle), and neutral sheet tilt angle (bottom).
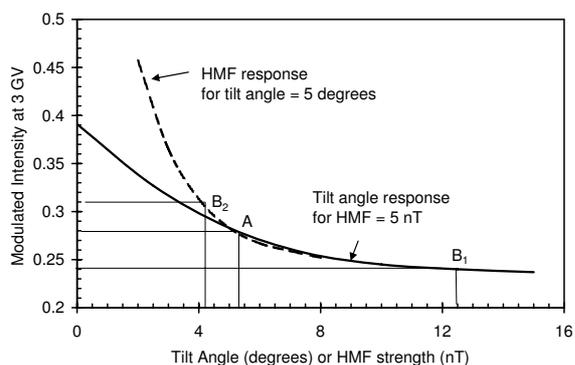

Fig. 4: Modulated intensity at Earth relative to the interstellar intensity at a rigidity of 3 GV, as function of the HMF (dashed line) and HMF tilt angle (full line), calculated from a numerical solution of the cosmic-ray transport equation, assuming that diffusion coefficients vary inversely proportional to the HMF. The line constructions indicate that the current (2009) conditions (points B1 and B2) can produce the same modulated intensity as in the very different solar minima of 22 and 44 years ago in 1987 and 1965 (point A).

that the parallel and perpendicular diffusion coefficients vary inversely proportional to the HMF, as described and motivated by Caballero-Lopez et al. [1], [2].

Point A in the figure represents conditions during the 1965 and 1987 minima, with a tilt angle of 5°, and an HMF of 5 nT. This produces a modulated intensity that is $\approx 35\%$ of the interstellar value. Likewise, points B1 and B2 represent conditions during the current (2009) minimum, with a tilt angle of 12°, and an HMF of 4.2 nT. These two variations respectively shift the modulated intensity down and up from the value at A, but by similar amounts. Hence, the intensities for conditions A and B

will be similar. This gives a natural explanation for the fact that the modulated intensity during the current solar minimum is similar to that of one and two solar magnetic cycles ago, despite the fact that the current modulating conditions are very different.

V. CONCLUSIONS

Using this comprehensive set of neutron monitor data we conclude that the alternating peak/plateau behaviour of subsequent cosmic-ray maxima is well-established, and that its different rigidity dependence for the overall modulation can be understood in terms of drift effects. Furthermore, the cosmic-ray levels have returned to nearly the same levels as during the previous two qA<0 solar minima, despite the fact that there are large differences in the heliospheric magnetic field and its tilt angle. We have demonstrated that this can be understood in terms of standard modulation theory.

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