

## Long-term neutron monitor observations and the 2009 cosmic ray maximum

H. Moraal<sup>1</sup> and P. H. Stoker<sup>1</sup>

Received 2 March 2010; revised 23 July 2010; accepted 29 July 2010; published 15 December 2010.

[1] The solar minimum of 2009 was characterized by a prolonged increase toward the maximum cosmic ray intensity, which was higher than it was during the maxima of 22 and 44 years ago. In the previous two so-called  $qA < 0$  (solar dipole moment facing South) magnetic cycles, these increases were more sharply peaked than in 2009. The observations of the Sanae, Hermanus, Potchefstroom, and Tsumeb neutron monitors are used to investigate this behavior in terms of propagation conditions due to solar activity, the heliospheric magnetic field, and the profile of the wavy current sheet in the field. This 2009 cosmic ray maximum can only be understood after an investigation of the long-term cosmic ray record. This study is augmented by observations of eight other neutron monitors. During 2009, solar activity parameters were significantly different from previous solar minima: The sun was much quieter, and the the heliospheric magnetic field was more than 20% weaker than during other recent minima. Both of these parameters imply a higher cosmic ray diffusion coefficient, which provides a natural explanation for both the higher galactic cosmic ray intensities that were observed and the absence of such an effect for anomalous cosmic rays.

**Citation:** Moraal, H., and P. H. Stoker (2010), Long-term neutron monitor observations and the 2009 cosmic ray maximum, *J. Geophys. Res.*, 115, A12109, doi:10.1029/2010JA015413.

### 1. Introduction

[2] 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 operated at one time or another. Currently, there are approximately 40 operating NMs in the worldwide network. They provide a long-term stable baseline for modulation studies. Details of this network were summarized in *Moraal et al.* [2000].

[3] The Unit for Space Physics operates 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 plot also shows data of the Sanae neutron moderated detector (NMD), which consists of a standard four-counter 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 by *Stoker et al.* [2000].

[4] The Hermanus NM has operated continuously since 1957, covering more than four 11-year solar modulation cycles, and hence more than two 22-year (Hale) solar magnetic cycles. The other NMs were established later. The data gap in 1995 and 1996 on the two Sanae detectors 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. This has greatly enhanced the stability of these detectors.

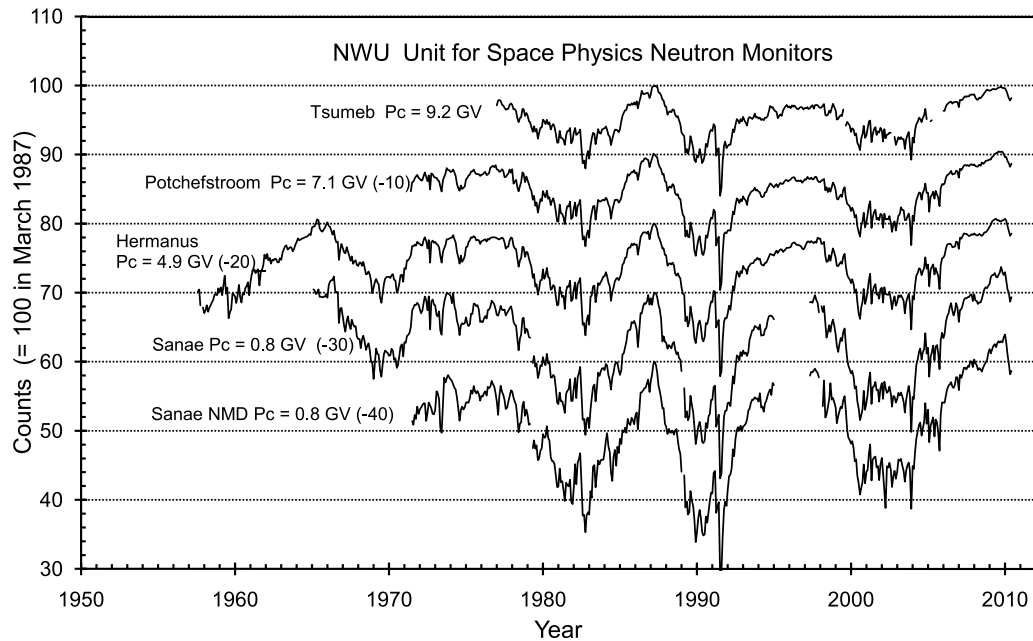
[5] This paper first evaluates this long-term cosmic ray record after the completion of another 22-year Hale cycle, and it then focuses on the cosmic ray intensity in the extraordinary quiet last (2009) solar minimum period.

### 2. Features of the Long-Term Modulation

[6] Figure 1 presents a long-term comprehensive overview of the cosmic ray modulation over the past 50 years. The cutoff rigidity ( $P_c$ ) dependence of the modulation is such that the modulation amplitude at Tsumeb at  $P_c = 9.2$  GV is  $\approx 15\%$  (when using monthly averages), while for the Sanae NMD at  $P_c = 0.8$  GV it is twice as large at  $\approx 30\%$ .

[7] The alternating peak-plateau pattern of the cosmic ray intensity has persisted at all stations since their inception: In May 1965 and in March 1987, the intensities reached well-defined peak values, while during the periods 1974 to 1977 and 1996 to 1997, there were much flatter, less sharply defined cosmic ray maxima. This behavior is understood in terms of drift of cosmic rays in the heliospheric magnetic field, as described for instance by *Moraal* [1993]: In 11-year periods such as from (about) 1960 to 1970, 1980 to 1990, and 2000 to the present, the solar and heliospheric magnetic fields in the northern hemisphere were generally pointed toward the sun and away in the southern hemisphere. These are so-called  $qA < 0$  periods. In the in-between  $qA > 0$  periods from 1970 to 1980 and 1990 to 2000, the field directions were reversed, with the reversals taking place about 1 year after sunspot maximum. Positively charged particles experience gradient and curvature drift in such a field so that the flow is directed

<sup>1</sup>Unit for Space Physics, School for Physical and Chemical Sciences, North-West University, Potchefstroom, South Africa.

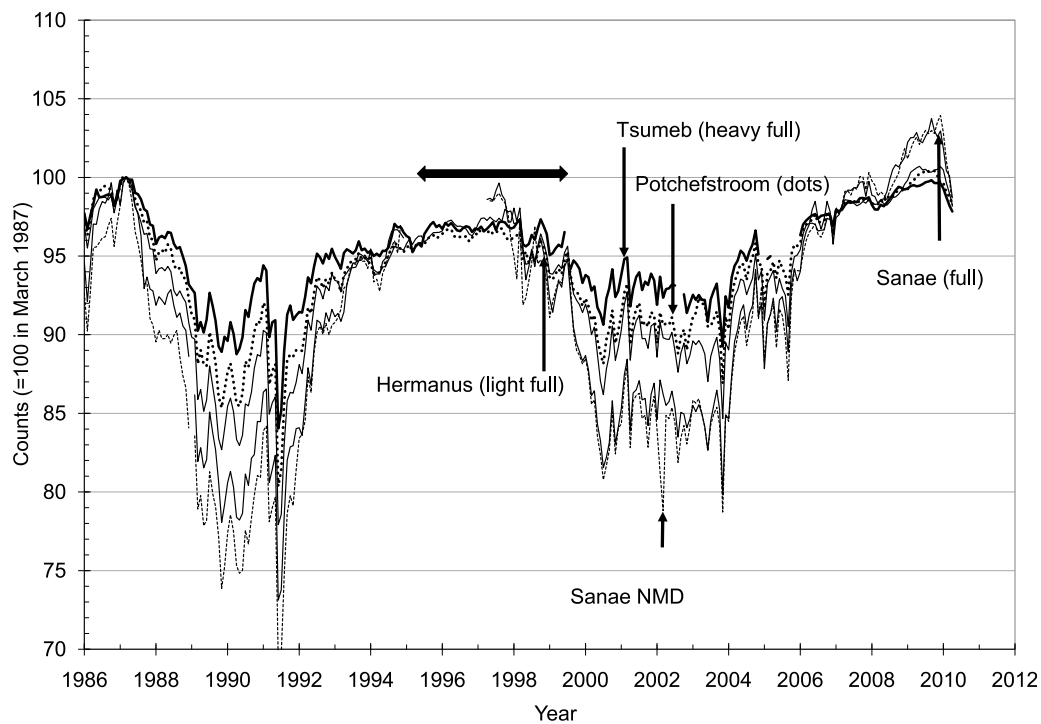


**Figure 1.** Monthly average counting rates of four NMs and a neutron moderated detector (NMD), normalized to 100 in March 1987. Offsets of  $-10$ ,  $-20$ ,  $-30$ , and  $-40$  are used to show the individual data sets.

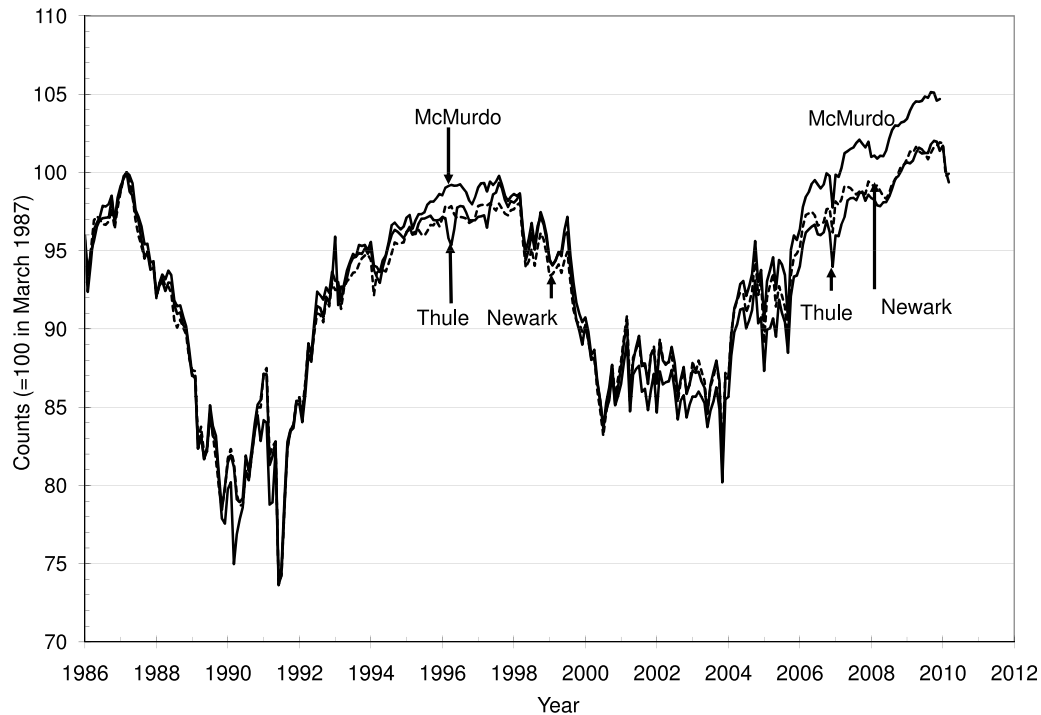
from pole to ecliptic and outward along the neutral sheet separating the hemisphere during the  $qA > 0$  periods, and oppositely during the  $qA < 0$  ones.

[8] This comprehensive, stable set of observations offers an excellent opportunity to study the long-term modulation, as well as the properties of the cosmic ray maximum in 2009.

[9] Figure 2 shows the same data as in Figure 1, but without the offsets. This emphasizes that the peak/plateau intensity ratios have a different rigidity dependence than the overall modulation cycle. While the overall modulation cycle on Sanae NMD is twice as large as that at Tsumeb (30% versus 15%), the  $qA > 0$  plateau intensities in August 1997 are 2.8%



**Figure 2.** The same as Figure 1, but without offsets. This emphasizes the properties of the  $qA > 0$  maximum, indicated by the horizontal double arrow from mid-1994 to mid-1998. Again, the counts are normalized to 100 in March 1987.



**Figure 3.** Counting rates of three neutron monitors of the Bartol Research Institute in the same format as in Figure 2.

below the March 1987  $qA < 0$  peak for Tsumeb, 3.3% for Potchefstroom, 2.6% for Hermanus, 1.0% for Sanae, and 0.4% for Sanae NMD. This means that these 1997 decreases relative to 1987 are of the same order of magnitude, with no clear rigidity dependence. If the rigidity dependence were the same as that for the overall modulation cycle, one would expect that if the 1997 deficit at Tsumeb was  $\sim 3\%$ , then at Sanae it should be  $\sim 6\%$ .

[10] This difference in rigidity dependence between the overall modulation cycle and the relative modulation during the  $qA > 0$  and  $qA < 0$  cosmic ray maxima extends to lower rigidities. To put this statement in context, we note that high-latitude neutron monitors have a geomagnetic cutoff rigidity  $P_c < 1$  GV, but an effective atmospheric cutoff  $P_c \approx 1$  GV. Their mean median rigidity of response is, however, much higher, with  $P_m \approx 16$  GV. Higher cutoff NMs have correspondingly higher values of  $P_m$ . *Svirzhevsky et al.* [2009] have reported on the long-term modulation of their daily stratospheric balloon flights at Moscow ( $P_c = 2.4$  GV) and Mirny and Murmansk ( $P_c \approx 1$  GV). These detectors have estimated values of  $P_m$  ranging from 5 to 7 GV. At these rigidities, they observe that the  $qA < 0$  peaks are at about the same level as the  $qA > 0$  plateaus. At even lower rigidities, e.g., for 1.1 to 1.8 GV (150 to 380 MeV/n) He, as measured on IMP8 and ACE by, e.g., *McDonald et al.* [2009], the  $qA > 0$  plateau intensities are higher than the  $qA < 0$  peak intensities. The same is true for 8 to 27 MeV/n ACR oxygen (average  $P = 1.2$  GV), as observed by *Leske et al.* [2009]. This rigidity-dependent pattern in the peak/plateau behavior led *Moraal et al.* [1989] and *Reinecke et al.* [1997] to suggest that the modulated spectra in opposite magnetic cycles should contain more than one crossover. (Such a crossover point is an energy or rigidity where one spectrum that lies below

another in a particular interval crosses to become higher than the other spectrum in an adjacent interval.) Such spectral features at neutron monitor energies have not yet been successfully modeled.

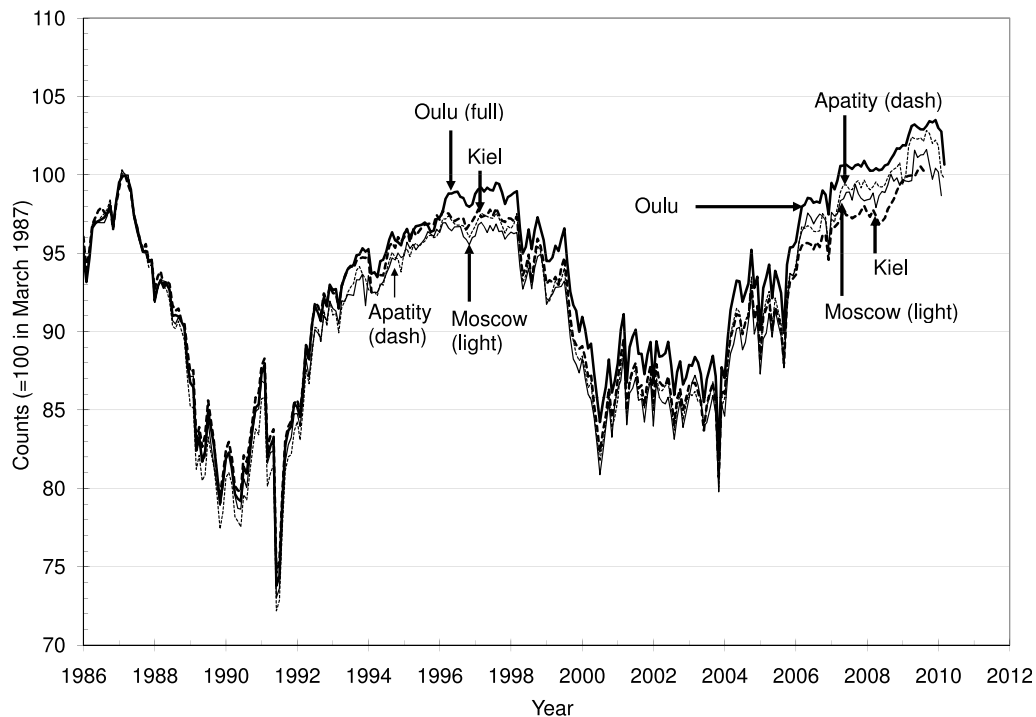
### 3. Features of the 2009 Cosmic Ray Maximum

[11] Next we focus on the current cosmic ray maximum, from about 2006 onward, which many authors have identified as being different from previous ones, as summarized by, e.g., *Moraal* [2009]. We note in Figure 2 that during this current cosmic ray maximum, the intensities at all four stations (plus the Sanae NMD) recovered to at least the 100% level, which is the normalization level used for March 1987. This cosmic ray maximum occurred in December 2009 on all five detectors.

[12] At some other NMs, the 2009/1987 counting ratios were significantly higher than for our stations. Figures 3 and 4 show the same plots as Figure 2 for three NMs of the Bartol Research Institute and four European ones, respectively. These peak counting rates in 2009, together with the month in which they occurred, relative to those in March 1987, are summarized Table 1 and Figure 5. We note that on four of the stations, the cosmic ray maxima occurred in October instead of December 2009.

[13] Table 1 and Figure 5 show the trend that the 2009 excess above 1987 decreases with rigidity, with the trendline given by the ratio of  $1.033P_c^{-0.015}$ .

[14] There is a significant scatter in these counting ratios, especially at the polar NMs plotted at 1 GV. This is probably due to systematic errors and environmental effects. NM count rates are influenced by (1) atmospheric pressure at a rate of  $\approx 1\%/mmHg$ , (2) atmospheric temperature at  $\approx 0.05\%/^{\circ}C$



**Figure 4.** Counting rates of four European neutron monitors in the same format as in Figure 2.

[*Jucci et al.*, 2000], and (3) instrumental temperature at  $+0.06\%/^{\circ}\text{C}$  [*Krüger et al.*, 2008; *Krüger and Moraal*, 2010]. Even after correction, these effects leave residual uncertainties. Apart from these known effects, there are also unknown environmental fluctuations due to, e.g., dynamic magnetospheric conditions, atmospheric water vapor (which contributes a highly variable  $\sim 1\%$  of atmospheric pressure), and snow effects. We note for instance that the Jungfraujoch NM has a high 2009/1987 ratio of 1.045, but its investigators treat this value with caution because the NM's long-term stability is subject to a continuously changing snow environment.

[15] As for the systematic errors, we express our confidence in the long-term stability of our five neutron monitors at Sanae (two), Hermanus, Potchefstroom, and Tsumeb. The quality controls have included daily manual pressure calibrations and a ratio check of each individual counter against the others in the particular monitor over all the years of

operation. When environmental and configuration changes had to be made, as at Sanae between 1994 and 1997, the proper renormalization was carefully calculated from the response of other similar neutron monitors.

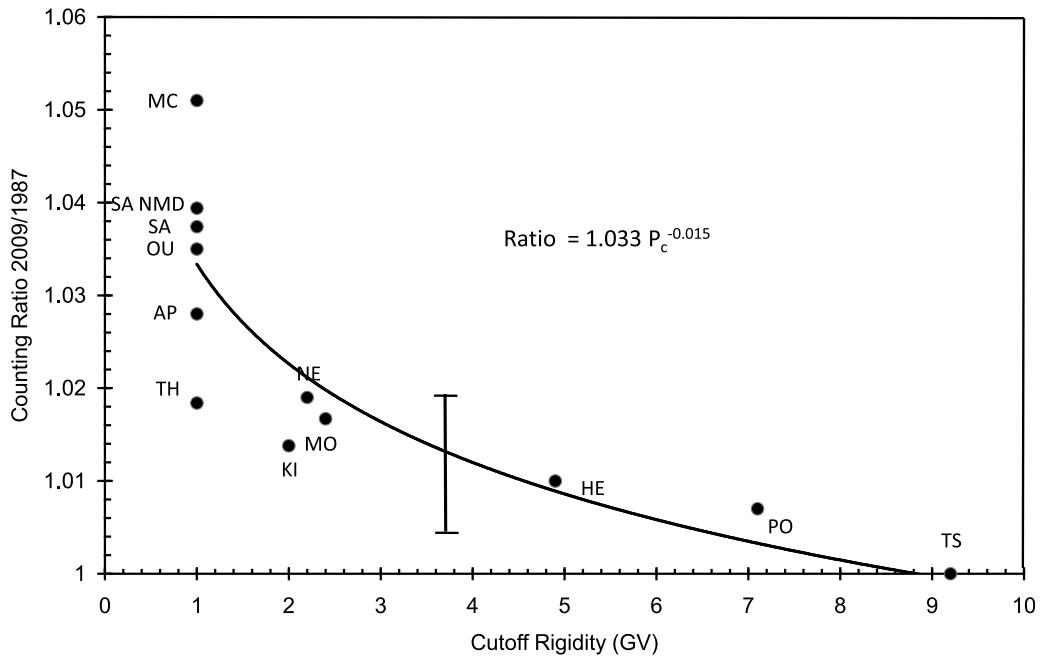
[16] We estimated the magnitude of these combined uncertainties by taking 150 values of monthly averaged count rates (from July 1997 to December 2009) of the six polar NMs plotted at 1 GV in Figure 5. Fifteen pairs of ratios of these count rates were calculated. Such ratios eliminate long-term modulation effects. The standard deviation of each of these ratios was calculated. The standard deviations range from  $\pm 0.5\%$  (McMurdo/Apatity) to  $\pm 1.8\%$  (Sanae/Oulu), with an average of 0.95%. The standard deviation of a single instrument is therefore taken as  $1/\sqrt{2}$  of the value for the ratio, or  $\pm 0.7\%$ . This error is shown by the vertical bar on the trend line in Figure 5. It shows that only the McMurdo NM lies significantly outside the band of the expected uncertainty.

[17] This rigidity-dependent trend continues to lower rigidities. *Svirzhevsky et al.* [2009] found, for instance, that the 2009 counting rates of their stratospheric balloon flights at Mirny, Murmansk, and Moscow were 11 to 16% higher than in 1987. These balloon flights are conducted at median rigidities of 5 to 6 GV, whereas the neutron monitors discussed above have median rigidities of response of  $\approx 16$  GV. Figure 6 plots these balloon flight points together with the NM points of Figure 5, but this time plotted as a function of median rigidity. The estimated uncertainty on the three balloon data points is  $\pm 1.5\%$  (about twice as large as that of NMs), which is shown by the vertical error bar. This combined data set confirms and extends the rigidity-dependent trend seen on the NMs.

[18] At even lower energies, *McDonald et al.* [2009] found that the 1.1 to 1.8 GV (180–250 MeV He) intensity in 2009 was 30% higher than in 1987, in agreement with this trend.

**Table 1.** Ratio of 2009 Counting Maxima Relative to That of March 1987 and Month in Which This Maximum Occurred

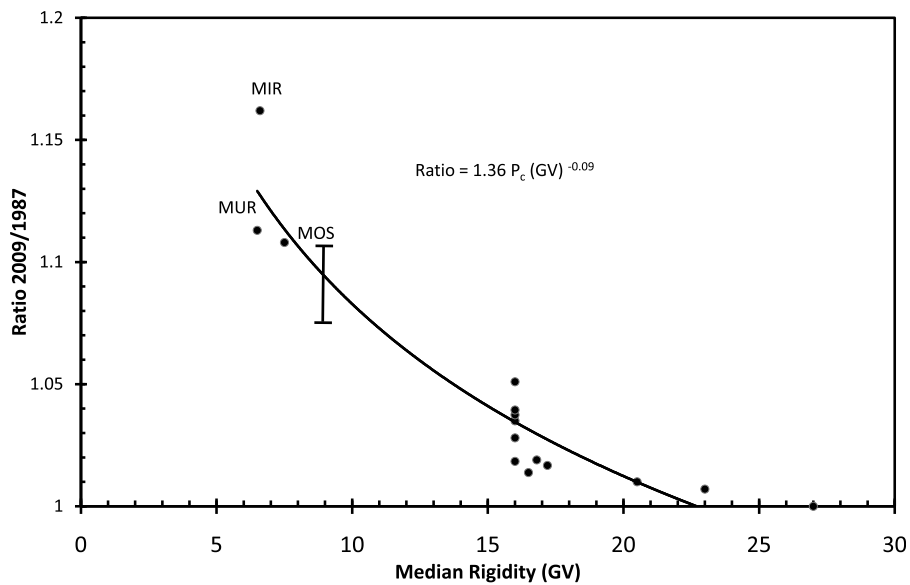
Station	$P_c$ (GV)	2009/1987	yyyy mm
Sanae NMD	<1.0	1.039	2009 12
Sanae	<1.0	1.037	2009 12
Thule	<1.0	1.018	2009 12
McMurdo	<1.0	1.051	2009 09
Apatity	<1.0	1.028	2009 09
Oulu	<1.0	1.035	2009 12
Kiel	2.0	1.014	2009 12
Newark	2.2	1.019	2009 09
Moscow	2.4	1.017	2009 09
Hermanus	4.9	1.010	2009 12
Potchefstroom	7.1	1.007	2009 12
Tsumeb	9.2	1.000	2009 12



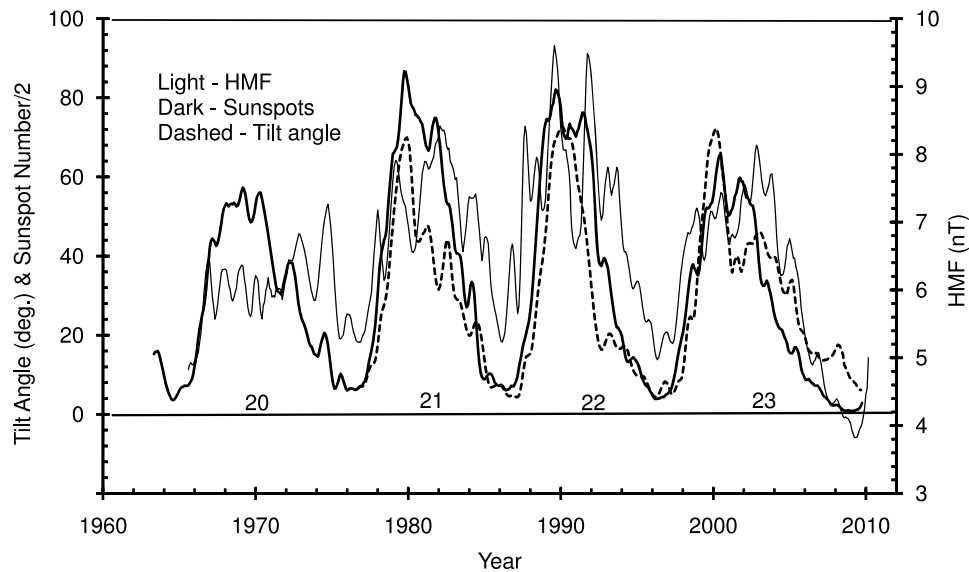
**Figure 5.** Counting ratios of 12 neutron monitors in 2009 relative to March 1987. The form of the power law best fit is shown. The error bar on the curve has a magnitude of  $\pm 0.7\%$  and is explained in section 3. See Table 1 for station abbreviations.

[19] On the other hand, *Leske et al.* [2009] reported that the 2009 anomalous cosmic ray (ACR) O intensity (average  $P = 1.2$  GV) was approximately the same as in 1987. This difference with the general trend is likely due to the fact that this species is anomalous. This was shown with the modeling results of *Steenberg* [1998] and *Steenberg and Moraal* [1999]: Less galactic cosmic ray (GCR) modulation is due

to a large diffusion mean free path, which is expected in a weak HMF as observed during the current minimum (as shown in the next paragraph). This larger mean free path, however, leads to a lower acceleration efficiency of ACRs by the solar wind termination shock. The modeling studies thus show that this reduces the rigidity where the spectra roll over from power laws to exponential cutoffs. Consequently, ACR



**Figure 6.** Counting ratios of the twelve neutron monitors shown in Figure 5 and three stratospheric balloon experiments (Moscow, Murnmansk, and Mirny) in 2009 relative to their counting rate in March 1987. The form of the power law best fit is shown. The error bar on the curve is for the three balloon flights and has a magnitude of  $\pm 1.5\%$ . The data points are plotted against estimated median rigidity, instead of cutoff rigidity as in Figure 5.



**Figure 7.** Nine-month running averages (weights 1, 2, 3, 4, 5, 4, 3, 2, 1) of the Zürich 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>).

intensities that are observed above this rollover rigidity, such as those of *Leske et al.*, are reduced.

[20] The rate of recovery toward the 2009 cosmic ray maximum was significantly slower than during the recoveries of one and two solar magnetic cycles ago. This is most clearly seen in Figure 1. The current double (22-year) modulation cycle is, however, only moderately longer than the previous one: The cosmic ray maxima of May 1965 and March 1987 occurred 21 years and 10 months apart, while the period from March 1987 to December 2009 covers 22 years and 9 months.

[21] In summary, therefore, neutron monitor observations, together with lower-energy measurements, reveal a cosmic ray excess in the 2009 solar minimum relative to the 1987 and 1965 minima that increases with decreasing energy or rigidity. The ACR intensity does not show a similar increase. These effects can be simultaneously understood by a larger diffusion coefficient due to the extraordinary low solar activity and small HMF during the 2009 minimum. This combined GCR/ACR effect must, however, still be modeled quantitatively.

#### 4. Modulating Agents During the 2009 Solar Minimum

[22] The differences in the modulation in this quiet period, when compared to previous minima, must be ascribed to differences in modulating agents between these cycles. The 2009 period of extraordinary low solar activity has been placed in the context of longer-term solar changes by, e.g., *Abreu et al.* [2008], *Lockwood et al.* [2009a, 2009b], *Lockwood* [2010], *Russell et al.* [2010], and *Vieira and Solanki* [2010]. Specifically, the sun has been in a so-called grand solar maximum state for the whole 50 years covered by this paper, and this maximum has lasted longer than most previous examples in the cosmogenic isotope record. The evidence suggests that the current low solar minimum arises

because this grand solar maximum is coming to its (overdue) end.

[23] Figure 7 is a combined plot of 9-month running averages of the Zürich sunspot number, the heliospheric magnetic field, and the tilt angle (classical value) between the heliographic and heliomagnetic axes that produces the wavy nature of the neutral sheet between oppositely pointing HMF directions. These three parameters are generally recognized as indicators of overall modulation strength. The turbulence in the HMF increases with increasing sunspot number and determines the cosmic ray diffusion coefficients parallel and perpendicular to the mean field, and hence the depth of modulation. It is also generally believed that the magnitude of these diffusion coefficients is inversely related to the strength of the HMF. (We note, however, that the HMF as presented is a convolution of the open solar flux that leaves the coronal source surface and the “processing” of this field by the solar wind between the source surface and the point of observation. Both of these are known to be position-dependent. The cosmic ray intensity will respond to the globally averaged HMF throughout the heliosphere. Hence, the field at 1 AU is only an approximate indicator of modulation strength.) Finally, it is a widely accepted standard feature of all modulation models that the waviness of the neutral sheet is a strong modulation agent during  $qA < 0$  cycles, especially near solar minimum.

[24] There are solar cycle variations in these parameters and also differences from one solar cycle to the next. These are not addressed in further detail 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 (averaged) value, i.e., the sunspot number to  $\approx 10$ , the HMF at Earth to  $\approx 5.5$  nT, and the tilt angle to  $\approx 5^\circ$ . However, during the 2009 solar minimum, the sunspot number was significantly lower than during these three previous minima, while the HMF dropped off to  $\approx 3.8$  nT instead of the usual 5.5 nT.

**Table 2.** Length of Solar Cycles in (averaged) Sunspot (SS) 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	13 06	13 10	13 08

[25] Table 2 also shows that for all three of these parameters, the previous cycle (23) was significantly longer than any of the prior three. The length of solar cycle 23 was 13 y 6 m in sunspot number, 13 y 10 m in HMF strength, and 13 y 8 m in tilt angle variations. This is 1 to 2 years longer than the previous three cycles. An analysis of *Kraiev and Kalinin* [2009] shows, however, that such long solar cycles are not so unusual. They find that of the 23 sunspot cycles observed so far, six were longer than 12 years.

[26] Figure 8 compares the Hermanus NM count rate with variations in these three parameters. The top of Figure 8 compares this count rate with sunspot number, the middle with HMF tilt angle, and the bottom with HMF strength. To aid visual comparison, the quantities are linearly transformed as noted in Figure 8 to give them approximately equal amplitude. Such plots reveal more detail than standard  $x$ - $y$  correlation plots. The top diagram shows the well-known result that the NM count 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 from 1987 to 1991, for instance, and the quality of correlation therefore varies. This leads to the well-known fact that solar activity as represented by sunspot number is a poor predictor of modulation. The middle of Figure 8 shows, however, that the correlation with tilt angle is not better, and the lower part of Figure 8 shows that with HMF strength it 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 was almost no

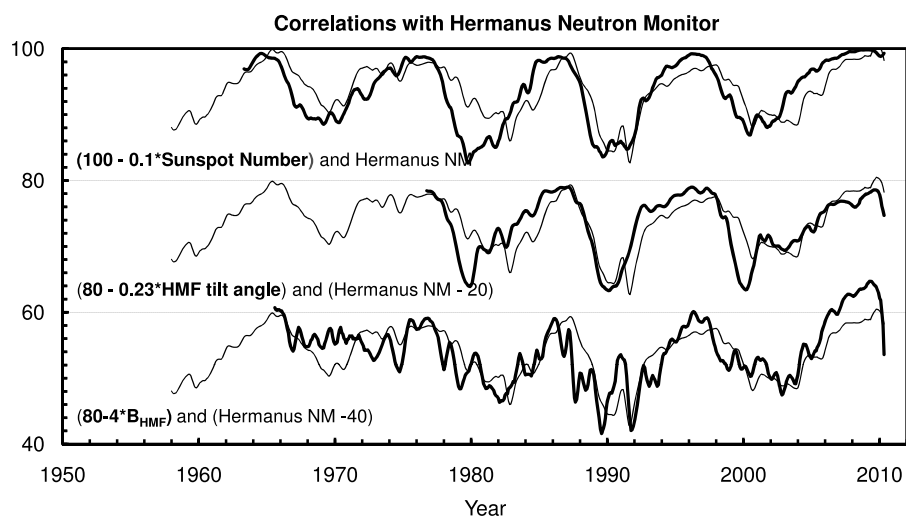
long-term field variation at all. There are also several periods in which the cosmic ray intensity actually leads the variations in the field.

[27] It remains a general practice to correlate cosmic ray intensity changes with changes in the HMF tilt angle. Comparison of the top and middle of Figure 8 shows that this has no more significance than the traditional, and discredited, practice to correlate it with sunspot number. These complex correlations demonstrate that the modulation is simultaneously controlled by a combination of these parameters, resulting in a time-dependent three-dimensional cosmic ray diffusion diffusion tensor.

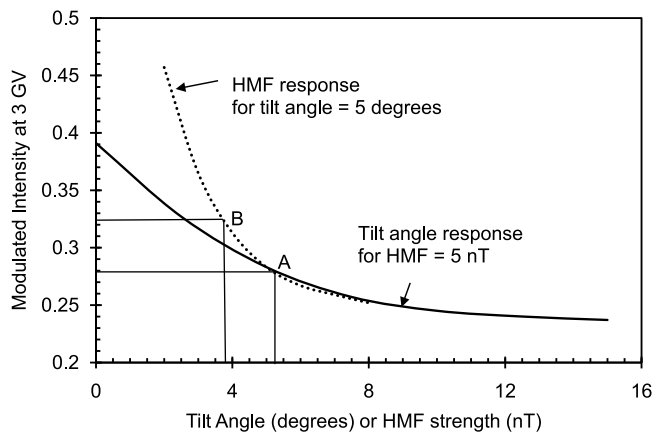
## 5. Modulation Calculation

[28] Finally, we ask whether the current level of modulation, which is less than the levels of March 1987 and May 1965 (Figure 1), can be understood quantitatively, in view of the large differences in HMF strength and the smaller differences in tilt angle when compared to these previous two solar minimum periods (Figure 7). 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.* [2004a]. The parameters of those solutions provide the best available fit to observations 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 *Caballero-Lopez et al.* [2004a] fits the intensities during solar minimum periods in the  $qA < 0$  solar magnetic cycle. We used the same parameters as for Figure 6 of *Caballero-Lopez et al.* [2004a], but instead of keeping the HMF (at Earth) fixed at 5 nT and the neutral sheet tilt angle at  $10^\circ$ , we calculated the amount of modulation as a function of these two parameters.

[29] The results are shown in Figure 9, which gives the modulated intensity at Earth relative to the interstellar intensity at a rigidity of 3 GV. The full line shows the intensity variation with tilt angle for a fixed value of the HMF. This is consistent with the well-known behavior that in a  $qA < 0$  cycle, the intensity near the ecliptic plane is a maximum,



**Figure 8.** Hermanus NM count rate (light lines) compared with linearly transformed values of the (top) sunspot number, (middle) heliospheric magnetic field, and (bottom) neutral sheet tilt angle.



**Figure 9.** 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 (solid line), calculated from a numerical solution of the cosmic ray transport equation, assuming that diffusion coefficients vary inversely proportional to the HMF. Points A and B indicate conditions typical of the 1965/1987 and the 2009 solar minima, respectively.

decreasing toward the poles, and that this maximum is at its strongest peak when the waviness of the neutral sheet is at its minimum. The dashed line shows the response to the strength of the HMF (for fixed tilt angle), assuming that the parallel and perpendicular diffusion coefficients vary inversely proportional to the HMF, as described and motivated by Caballero-Lopez *et al.* [2004a, 2004b].

[30] Point A in Figure 9 represents conditions that are typical of the 1965 and 1987 solar minima, with a tilt angle of approximately  $5^\circ$  and an HMF of 5.5 nT. This produces a modulated intensity (at 3 GV) that is  $\approx 28\%$  of the interstellar value. The 2009 solar minimum is characterized by a tilt angle that is about the same as in the previous minima, or somewhat larger. This reduces the 2009 intensity relative to the intensities in the  $qA < 0$  solar minima of 1987 and 1965. However, the HMF decreased to 3.8 nT, which causes a significant increase in intensity as marked by point B. Thus the stronger HMF dependence gives a natural explanation for the fact that the modulated intensity during the 2009 solar minimum was higher than that during one and two solar magnetic cycles ago.

[31] The rigidity used for this calculation is significantly lower than the median rigidity of response of NMs, namely 16 GV. The 2004 calculations used here were not set up for these higher rigidities. Our next step therefore is to model this effect in greater detail as a function of rigidity, for all the NM, balloon-borne and spacecraft observations in this paper.

## 6. Conclusions

[32] Using a comprehensive set of neutron monitor data, we conclude that the alternating peak-plateau behavior of subsequent cosmic ray maxima is well established and that its different rigidity dependence from the overall modulation can be ascribed to the different combination of drift effects with convection and diffusion in the  $qA > 0$  and  $qA < 0$  cycles. The high peaks and low plateaus, with the reversed pattern at lower energies, have not been modeled satisfactorily yet.

[33] Furthermore, during the 2009 solar minimum, cosmic ray levels as recorded by neutron monitors recovered to statistically significant higher values than during the previous two  $qA < 0$  solar minima in 1987 and 1965. This is consistent with the higher cosmic ray intensities observed during the sunspot minima of 1944 and 1933 and those evident in the cosmogenic record of the Gleissberg, Dalton, Maunder and Spörer minima. This effect is strongly rigidity-dependent, with the highest rigidities showing no excess over the previous minima. We believe that this excess is due to the fact that both the HMF and the sunspot number were significantly lower than in those earlier minima. Both of these quantities lead to a natural increase in the diffusion coefficient, which increases the intensity of galactic cosmic rays, but at the same time has an opposite effect on the intensity of anomalous cosmic rays. We believe that differences in the geometry of the neutral sheet during the 2009 solar minimum relative to the earlier ones was less important for these different modulation effects.

[34] In this sense, the cosmic ray maximum of 2009 can be understood in terms of standard modulation theory. This now needs to be quantified with full numerical solutions of the cosmic transport equation for all the neutron monitors and space experiments combined.

[35] **Note added in proof.** It has been brought to our attention that the renormalization of the Sanae neutron monitors from 1994 to 1997 was indeed done inadequately. The entry for Sanae in Table 1 should change from 1.017 to 1.037, and that for Sanae NMD should change from 1.019 to 1.039. This changes the coefficient of the trend line in Figure 5 from 1.027 to 1.033, but the power of  $-0.01$  is unaffected. The trend line of Figure 6 is insignificantly affected. This change will be explained in a subsequent communication.

[36] **Acknowledgments.** We gratefully acknowledge the dedicated service of A. Benadie, A. D. Mans, and R. E. Smit to keep our neutron monitors running smoothly and producing high-quality data over many years. The use of data of other neutron monitors and stratospheric balloon data is gratefully acknowledged. Neutron monitors of the Bartol Research Institute are supported by National Science Foundation grant ATM-0527878. Constructive comments from two reviewers, especially about the longer-term significance of the current solar minimum, have enhanced the quality of this paper.

[37] Philippa Browning thanks Kenneth McCracken and Michael Lockwood for their assistance in evaluating this paper.

## References

- Abreu, J. A., J. Beer, F. Steinhilber, S. M. Tobias, and N. O. Weiss (2008), For how long will the current grand maximum of solar activity persist?, *Geophys. Res. Lett.*, *35*, L20109, doi:10.1029/2008GL035442.
- Caballero-Lopez, R. A., H. Moraal, and F. B. McDonald (2004a), Galactic cosmic-ray modulation: effects of the solar wind termination shock and the heliosheath, *J. Geophys. Res.*, *109*, A05105, doi:10.1029/2003JA010358.
- Caballero-Lopez, R. A., H. Moraal, K. G. McCracken, and F. B. McDonald, (2004b), The heliospheric magnetic field from 850 to 2000 inferred from  $^{10}\text{Be}$  records, *J. Geophys. Res.*, *109*, A12102, doi:10.1029/2004JA010633.
- Iucci, N., G. Villaresi, L. I. Dorman, and M. Parisi (2000), Cosmic ray survey to Antarctica and coupling functions for neutron component near solar minimum (1996–1997), 2. Determination of meteorological effects, *J. Geophys. Res.*, *105*(A9), 21,035–21,045, doi:10.1029/2000JA900050.
- Kraevnev, M., and M. Kalinin (2009), On the current phase of the solar cycle in the solar and heliospheric parameters and GCR intensity, *Proc. 31st Int. Cosmic-ray Conf.*, Lodz, paper 1043.



- Krüger, H., and H. Moraal (2010), A calibration neutron monitor: statistical accuracy and environmental sensitivity, *Adv. Space Res.*, doi:10.1016/j.asr.2010.07.008, in press.
- Krüger, H., H. Moraal, J. W. Bieber, J. M. Clem, P. A. Evenson, K. R. Pyle, M. Duldig, and J. E. Humble (2008), A calibration neutron monitor: energy response and instrumental temperature sensitivity, *J. Geophys. Res.*, *113*, A08101, doi:10.1029/2008JA013229.
- Leske, R. A., A. C. Cummings, C. M. S. Cohen, R. A. Mewaldt, E. C. Stone, M. E. Wiedenbeck, and T. T. von Rosenvinge (2009), The unusual behavior of anomalous and galactic cosmic ray intensities at 1 AU during the present solar minimum, *Proc. 31st Int. Cosmic-ray Conf.*, Lodz, paper 536.
- Lockwood, M. (2010), Solar change and climate: an update in the light of the current exceptional solar minimum, *Proc. R. Soc. Lond. A*, *466*, 303–329.
- Lockwood, M., A. P. Rouillard, and I. D. Finch (2009a), The rise and fall of open solar flux during the current grand solar maximum, *Astrophys. J.*, *700*, 937–944, doi:10.1088/0004-637X/700/2/937.
- Lockwood, M., M. Owens, and A. P. Rouillard (2009b), Excess Open Solar Magnetic Flux from Satellite Data: II. A survey of kinematic effects, *J. Geophys. Res.*, *114*, A11104, doi:10.1029/2009JA014450.
- McDonald, F. B., W. R. Webber, and D. V. Reames (2009), The unusual time history of galactic and anomalous cosmic rays at 1 AU over the solar minimum of cycle 23, *Proc. 31st Int. Cosmic-ray Conf.*, Lodz, paper 480.
- Moraal, H. (1993), Cosmic ray modulation studies in the outer heliosphere, *Nuclear Phys. B. (Proc. Suppl.)*, *33A,B*, 161.
- Moraal, H. (2009), Galactic cosmic rays in the heliosphere, *Proc. 31st Int. Cosmic-ray Conf.*, Lodz, rapporteur paper.
- Moraal, H., M. S. Potgieter, P. H. Stoker, and A. J. van der Walt (1989), Neutron monitor latitude survey of the cosmic ray intensity during the 1986/87 solar minimum, *J. Geophys. Res.*, *94*, 1459, doi:10.1029/JA094iA02p01459.
- Moraal, H., A. Belov, and J. M. Clem (2000), Design and co-ordination of multi-station international neutron monitor networks, *Space Sci. Rev.*, *93*, 285.
- Reinecke, J. P. L., H. Moraal, M. S. Potgieter, F. B. McDonald, and W. R. Webber (1997), Different crossovers?, *Proc. 25th Int. Cosmic-ray Conf.*, *2*, 49.
- Russell, C. T., J. G. Luhmann, and L. K. Jian (2010), How unprecedented a solar minimum?, *Rev. Geophys.*, *48*, RG2004, doi:10.1029/2009RG000316.
- Steenberg, C. D. (1998), Modelling of the intensity of galactic and anomalous cosmic rays in the outer heliosphere, Ph.D. thesis, Potchefstroom University for CHE.
- Steenberg, C. D., and H. Moraal (1999), The form of the anomalous cosmic ray spectrum at the solar wind termination shock, *J. Geophys. Res.*, *104*, 24,879–24,884, doi:10.1029/1999JA900336.
- Stoker, P. H., L. I. Dorman, and J. M. Clem (2000), Neutron monitor design improvements, *Space Sci. Rev.*, *93*, 361.
- Svirzhevsky, N. S., G. A. Bazilevskaya, V. S. Makhmutov, Y. I. Stozhkov, and A. K. Svirzhevskaya (2009), Low energy ( $E > 100$  MeV) galactic cosmic rays in the prolonged activity minimum of the 24th solar cycle according to stratospheric measurements, *Proc. 31st Int. Cosmic-ray Conf.*, Lodz, paper 1105.
- Vieira, L. E. A., and S. K. Solanki (2010), Evolution of the solar magnetic flux on time scales of years to millennia, *Astron. Astrophys.*, *509*, A100.

---

H. Moraal and P. H. Stoker, Unit for Space Physics, School for Physical and Chemical Sciences, North-West University, Potchefstroom 2520, South Africa. (harm.moraal@nwu.ac.za; pieter.stoker@nwu.ac.za)