Record neutron monitor counting rates from galactic cosmic rays

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[1] Neutron monitors have recorded the flux of high-energy Galactic cosmic rays for more than half a century. During the recent, prolonged, deep minimum in solar activity, many sources indicate that modulated Galactic cosmic rays have attained new Space Age highs. However, reported neutron monitor rates are ambiguous; some record new highs while others do not. This work examines the record of 15 long-running neutron monitors to evaluate cosmic ray fluxes during the recent extraordinary solar minimum in a long-term context. We show that ground-level neutron rates did reach a historic high during the recent solar minimum, and we present a new analysis of the cosmic ray energy spectrum in the year 2009 versus year 1987. To do this, we define a reference as the average of eight high-latitude neutron monitors, four in the Northern Hemisphere (Apatity, Inuvik, Oulu, Thule) and four in the Southern Hemisphere (Kerguelen, McMurdo, Sanae, Terre Adelie). Most stations display changes in sensitivity, which we characterize by a simple linear trend. After correcting for the change in sensitivity, a consistent picture emerges. With our correction, all stations considered display new highs at the recent solar minimum, approximately 3% above the previous record high. These increases are shown to be consistent with spacecraft observations.

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1. Introduction

[2] According to sensors on NASA's ACE (Advanced Composition Explorer) spacecraft, Galactic cosmic ray fluxes reached a Space Age high in late 2009 [*Mewaldt et al*., 2010] with intensities at about 200 MeV/nucleon fully 20% higher than previously observed. *Ahluwalia and Ygbuhay* [2010] noted that neutron monitors were also at a record high. *Moraal and Stoker* [2010] discussed the maximum in the context of long-term neutron monitor observations.

[3] On closer examination, neutron monitors seem to disagree about whether there was a Space Age record. Figure 1 shows the count rates of McMurdo and Thule since 29 July 1964 as 27 day averages using the Bartels rotation period. McMurdo data clearly indicate a Space Age record, but the data from Thule are ambiguous. Other reported neutron monitor rates are mixed; some record a new high and others do not [*Oh et al*., 2010; *Ahluwalia and Ygbuhay* 2012]. In order to resolve this confusion, we have examined the record of 15 long-running middle and high-latitude neutron monitors in some detail.

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2. Data and Method

[4] Overall, we considered data from 15 neutron monitor stations with cutoff rigidity less than approximately 6 GV which had long-term data sets extending back to at least 1964. For our study, we selected data from Bartels rotation 1793 (starting 29 July 1964) to rotation 2420 (ending 30 December 2010). Table 1 shows the basic characteristics of these neutron monitor stations. Geographic latitude and longitude, cutoff rigidity, altitude, and monitor type were obtained from the web sites of the various stations, many of which changed configuration and location over the time interval considered in this report. Magnetic latitude and longitude were calculated from the geographic location using the International Geomagnetic Reference Field model appropriate for 2010 (http://wdc.kugi.kyoto-u.ac.jp/igrf/gggm/index.html). We created a reference data set by averaging eight high-latitude neutron monitor stations, four in the Northern Hemisphere (Apatity, Inuvik, Oulu, Thule) and four in the Southern Hemisphere (Kerguelen, McMurdo, Sanae, Terre Adelie). The geomagnetic cutoffs for all reference stations are less than 1.2 GV; therefore, we expect them to be minimally affected by secular changes in the magnetic field of Earth. Data since 2006 from the stations at Kerguelen and Terre Adelie (http://www.nmdb.eu/nest) have not been verified and were not included in the preparation of the reference set though we do include them in our discussion below of the 2009 cosmic ray maximum.

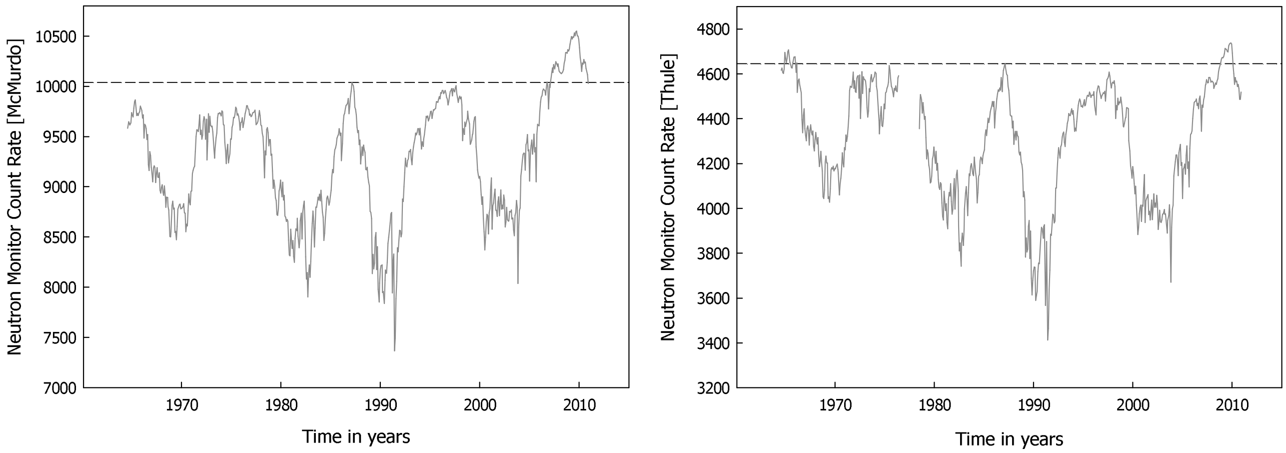


Figure 1. Bartels rotation averaged neutron monitor count rate at (left) McMurdo and (right) Thule.

[5] In Figure 2, we display the reference calculated from the average of eight high-latitude neutron monitor stations, normalized to 100% at the 1987 maximum, as a function of time. The reference returns to nearly the same level in the flat maxima in the 1970s and 1990s. It also returns to similar, but higher, levels in the first two peaked maxima. However, the level attained in 2009 is much higher, suggesting that there was indeed a new record level about 3.4% above the old one.

[6] We compare individual neutron monitor records to this apparently stable reference in order to better characterize long-term trends in their counting rates. We do this by fitting a straight line to the ratio of the station to the reference. Figure 3 shows the resulting trends at our own McMurdo and Thule neutron monitor stations. McMurdo has a positive trend, and Thule has a negative trend with respect to the reference. Currently, we do not understand the source of these changes, nor are we certain that they are linear. However, for the purposes of this analysis, we find that considering the trend at all stations to be linear is adequate to quantify the rather abrupt increase in 2009.

[7] In Table 2, we show the result of the trend analysis for each neutron monitor station. First, we present the coefficients of the trend line. Some stations have positive and some stations have negative trends with respect to the reference. To put this in perspective, we express the same information in terms of the total change since 1964 and also the total change since 1987. In this analysis, errors due to counting statistics are negligible. We only consider Bartels rotation averages of neutron monitor counting rates and the lines are fitted to hundreds of points. Statistical errors on either the points or the fits would not be visible in Figure 3. As can be seen in Figure 3, the scatter about the lines appears to have both random and systematic components. We do not attempt to differentiate between them. Instead, we simply quantify the scatter about the trend line in terms of the standard deviation of the points from the line. Note that the standard deviations for the midlatitude stations tend to be larger than those for the high-latitude stations. The reference is constructed entirely from high-latitude stations so it has a larger overall response to solar modulation than that of the higher cutoff stations, contributing extra deviation from the trend line for the higher cutoffs.

[8] Using the trend lines, we can then detrend the count rates at all stations. Figure 4 shows, as an example, the results of detrending McMurdo and Thule.

3. Results

[9] A consistent picture emerges in the detrended data for all stations; namely, all attain a historical record level

Table 1. Characteristics of 15 Neutron Monitor Stations Used in our Study

Neutron Monitor Station	Geographic Latitude(°)	Geographic Longitude (°)	Geomagnetic Latitude (°)	Geomagnetic Longitude (°)	P_c (GV)	Altitude (m)	Type of Neutron Monitor
Apatity	67.55	33.33	63.06	125.25	0.65	177	18NM64
Hermanus	−34.42	19.23	−33.90	84.68	4.90	26	12NM64
Inuvik	68.35	226.28	70.95	272.35	0.18	21	18NM64
Jungfraujoch	46.55	7.98	47.15	90.82	4.48	3475	12IGY
Kerguelen	−49.35	70.27	−56.62	133.64	1.14	33	18NM64
Lomnicky	49.20	20.22	47.61	103.59	4.00	3400	8NM64
McMurdo	−77.95	166.60	−79.03	289.14	0.01	48	18NM64
Moscow	55.47	37.32	50.95	121.60	2.46	200	24NM64
Newark	39.70	284.30	49.48	355.87	1.97	50	9NM64
Oulu	65.05	25.47	61.89	116.86	0.81	0	9NM64
Rome	41.90	12.52	41.85	93.69	6.32	60	18NM64
Sanae	−71.67	357.15	−66.20	47.19	1.06	856	6NM64
Terre Adelie	−66.67	140.02	−74.11	230.89	0.02	45	9NM64
Thule	76.60	291.20	86.43	12.91	0.00	260	18NM64
Yakutsk	62.01	129.43	52.40	196.58	1.70	105	18NM64

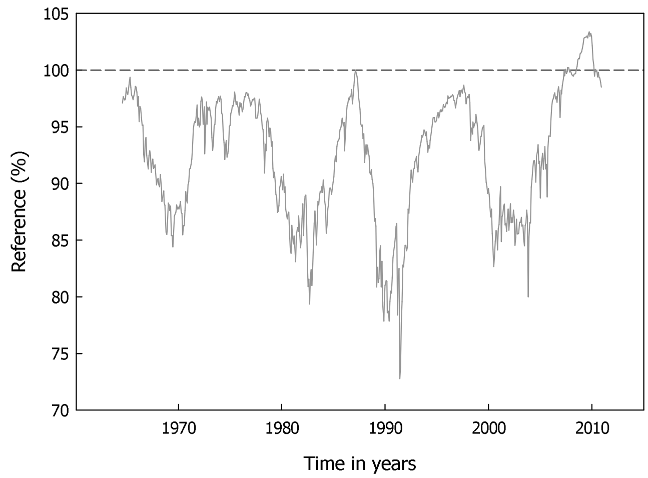


Figure 2. Reference derived from the average of eight high-latitude neutron monitor stations normalized to 100% at the 1987 maximum.

sometime in 2009. We express this maximum in terms of excess above the trend line. Table 3 gives the maximum value of the excess, together with the Bartels rotation number during which the excess was a maximum, for each station. In Figure 5, we display the excess in the detrended data as a function of the geomagnetic cutoff of the station in two ways. First, we show the excess at the time of the maximum of the reference, which was Bartels rotation 2404. Then we show the absolute maximum for each station at the time at which the maximum occurred. We note that the excesses appear systematically larger for the high-latitude stations; however, there is considerable scatter.

[10] In order to explore the systematics of a possible relationship, we construct a simple model of the relative excess (Δj) in differential intensity, j, to be a power law in rigidity:

$$\frac{\Delta j}{j} \equiv \frac{j_{09} - j_{87}}{j_{87}} = KP^{-\eta} \tag{1}$$

with rigidity P in units of GV. Here and below, the subscripts "09" and "87" denote quantities at the times of the cosmic ray maxima in 2009 and 1987, respectively.

[11] The count rate of a neutron monitor, C, can be determined from differential intensity by multiplying by the specific yield function, $S(P)$, and integrating over rigidity,

$$\frac{\Delta C}{C} \equiv \frac{C_{09} - C_{87}}{C_{87}} = \frac{1}{C_{87}} \int_{P_c}^{\infty} \Delta j(P) S(P) dP \tag{2}$$

where P_c is the cutoff rigidity of the neutron monitor.

[12] For this work, it is convenient to use a specific yield function derived from neutron monitor latitude surveys of cosmic ray intensity during the 1986/1987 solar minimum by *Moraal et al.* [1989]. Denoting the latitude survey results by $N_{87}(P_c)$, equation (2) can be recast as

$$\frac{\Delta C}{C} = \frac{1}{C_{87}} \int_{P_c}^{\infty} \frac{\Delta j}{j_{87}} \left[-\frac{dN_{87}}{dP} \right] dP, \tag{3}$$

where the term in square brackets, $-dN_{87}/dP$, is the differential response function in 1987.

[13] For a specific form of the differential response function, we used the regression coefficients of the Dorman function [*Dorman et al.*, 1970] representation of data taken with monitors installed on the commercial vessels Vaal and

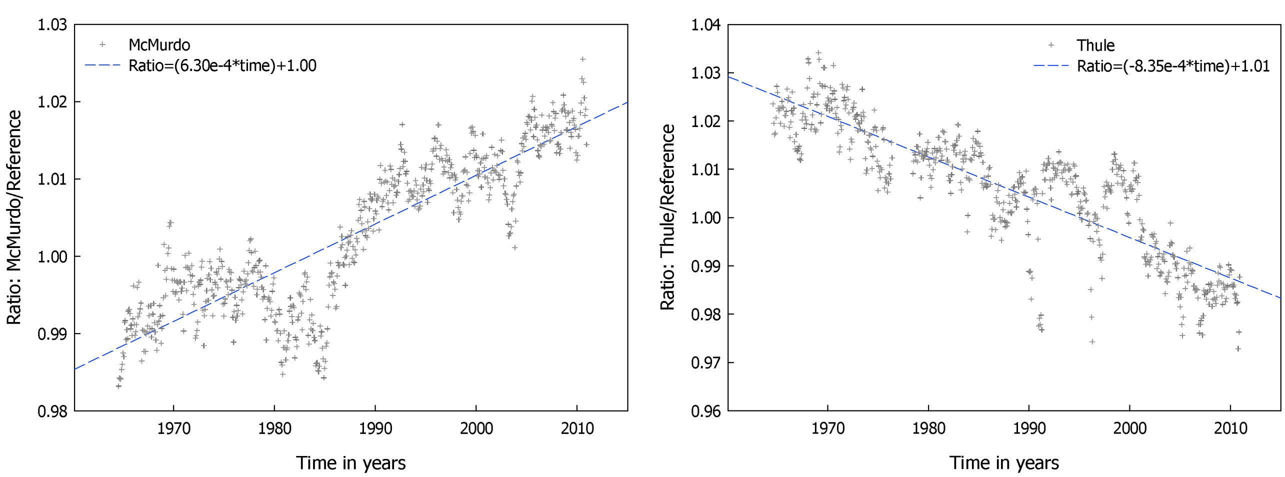


Figure 3. Ratio of Bartels rotation averages of McMurdo and Thule neutron monitor counting rates to the reference as a function of time. Linear trend lines are fit to the data.

Table 2. Linear Trend Analysis for 15 Neutron Monitor Stations

Neutron Monitor Station	Linear Trend in Monitor to Reference Ratio: A·Time + B				
	10^4 A [year^{-1}]	B	Total Change (%) 1964–2009	Total Change (%) 1987–2009	Standard Deviation (%)
Apatity	−6.29	1.00	−2.9	−1.5	0.70
Hermanus	−7.47	1.02	−3.3	−1.7	1.74
Inuvik	−1.86	1.01	−0.9	−0.4	0.49
Jungfraujoch	−3.58	1.00	−1.6	−0.9	2.03
Kerguelen	2.03	1.00	0.9	0.5	0.39
Lomnicky	−11.2	1.00	−5.1	−2.7	2.01
McMurdo	6.30	1.00	3.0	1.5	0.49
Moscow	−6.38	1.00	−2.9	−1.5	0.82
Newark	−0.80	1.00	−0.4	−0.2	0.76
Oulu	2.84	1.01	1.3	0.7	0.60
Rome	−2.38	1.02	−1.1	−0.6	2.90
Sanae	5.96	0.99	2.8	1.4	0.67
Terre Adelie	−2.50	0.99	−1.2	−0.6	0.74
Thule	−8.35	1.01	−3.8	−2.0	0.67
Yakutsk	−5.23	1.00	−2.4	−1.2	1.83

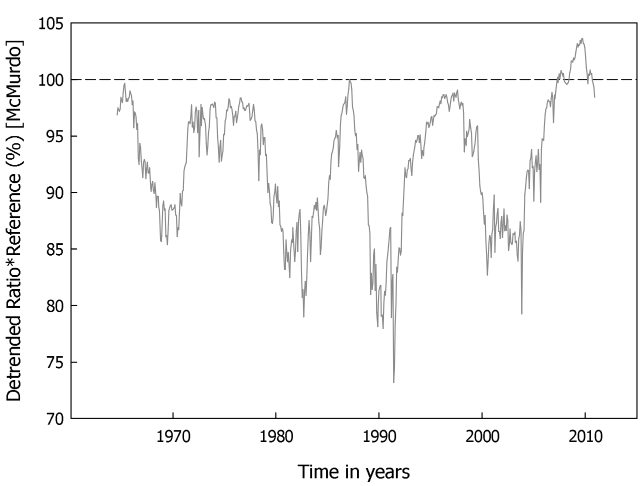
Vento: $N_o = 147.45$, $k = 0.9644$, $\alpha = 10.446$ (Note that the Dorman function k is distinct from the spectrum K appearing in equation (1)). Since the Dorman function gives the counting rate as a function of cutoff rigidity, we then express the differential response function for 1987, which is the negative derivative of the Dorman function, in the form proposed by *Moraal et al*. [1989],

$$-\frac{dN_{87}}{dPc} = \alpha k(N_0 - N_{87})P_c{}^{-k-1} \quad (4)$$

[14] Finally, substituting equation (1) into equation (3), we obtain an expression for the observed quantity $\Delta C/C$ in terms of two unknowns K and η.

[15] Values of $\Delta C/C$ for 15 neutron monitors appear in the last column of Table 3. By using a simple grid search of the two-dimensional parameter space defined by K and η and integrating equation (3) numerically, we determined the minimum value of chi-square (χ^2) in a fit to all stations simultaneously. In this fit, we estimated the variance appropriate to each station from the standard deviation in Table 2. The left panel of Figure 5 shows the result for the case where all the excesses are measured at the maximum of the reference. Here the parameters $K = 2.39$ and $\eta = 2.18$ provide the best fit to the increases. This best fit is shown as a solid red line. With a nearly nominal chi-square of 13.62 for 13 degrees of freedom, this simple model clearly characterizes the dependence of the excess on geomagnetic cutoff. Alternatively, if we do the same fit using the maximum at each station independently, we obtain the result in the right panel. This has slightly less scatter from the line, but the two approaches yield essentially the same fitted curve. However, the optimal K, η pairs (shown at upper right of the plot panels) are rather different.

[16] It is difficult to make a quantitative evaluation of the scatter from the curve or to make specific statements as to whether it results from physical effects or from calibration or stability problems at the individual stations. Even exhaustive efforts to understand long-term stability of neutron monitors often produce inconclusive results [*Bieber et al*., 2007]. We have done some simple tests to see if there is a systematic trend to the scatter, but these have been inconclusive. In



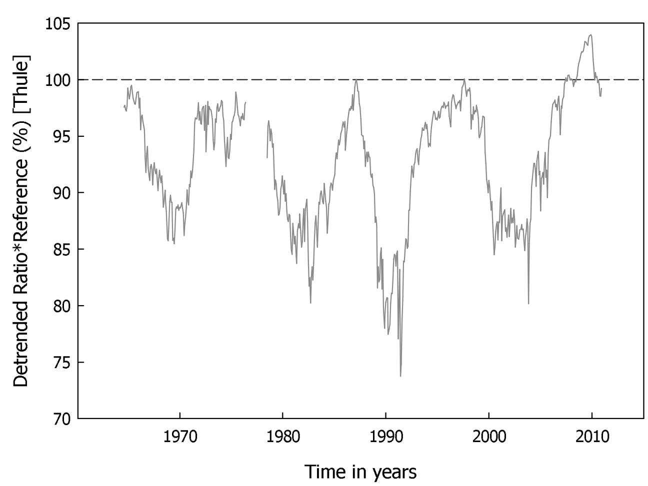


Figure 4. Detrended count rates at McMurdo and Thule neutron monitor stations, normalized to 100% on 14 February 1987.

Table 3. Excess Over the Trend Line at the Beginning of Solar Cycle 24

Neutron Monitor Station	P_c (GV)	Recent Maximum		Excess (%) at BR2404
		Bartels Rotation	Excess (%)	
Apatity	0.65	2404	4.3	4.3
Hermanus	4.90	2406	2.4	2.2
Inuvik	0.18	2406	3.5	3.4
Jungfraujoch	4.48	2406	1.1	0.9
Kerguelen	1.14	2406	2.9	2.7
Lomnicky	4.00	2401	1.0	1.0
McMurdo	0.01	2404	3.6	3.6
Moscow	2.46	2403	3.3	2.9
Newark	1.97	2407	2.4	2.0
Oulu	0.81	2406	3.0	2.9
Rome	6.32	2397	1.2	1.2
Sanae	1.06	2401	2.6	2.5
Terre Adelie	0.02	2406	1.9	1.6
Thule	0.00	2406	4.0	3.9
Yakutsk	1.70	2398	3.1	2.9

particular, there is little, if any, tendency for the deviations to be larger for those stations with larger corrections.

[17] In Figure 6, we explore the implications of our fit. The black cross shows the values of K and η which provide the best fit to the neutron monitor data for the case shown in the left panel of Figure 5, while the contours show allowed regions permitted with increasing values of χ^2. The data provide a tight constraint in parameter space on the two parameters describing the spectral change jointly but not individually. In other words, the neutron monitor observations by themselves do not identify a unique combination of K and η, but rather, they identify a narrow "allowed region" of parameter space within which acceptable combinations of K and η reside.

[18] We also show the results of alternate analyses in Figure 6. The square shows the optimum combination from the right panel of Figure 5. We have also done the fit assuming the same variance for all stations. In other words, this is a simple least squares fit, in contrast to Figure 5 where the individual station contributions to χ^2 were weighted by each station's individual variance. The triangle shows the results for the excesses at rotation 2404 while the circle represents the fit to the absolute maximum at each station. In all cases, the parameters determined are consistent with our definition of the allowed region.

[19] To determine specific values for K and η, additional observational constraints are required, and for this, we turn to spacecraft data. From equation (1), a single value of $\Delta j/j$ at a specific rigidity does not define a unique combination of K and η; rather, it defines a line in the plane displayed in Figure 6. The solid line is the locus of values of K and η that produce the observed [*Mewaldt et al.*, 2010] increase in the iron flux at 360 MeV/nucleon (1.93 GV) of 16%, while the dashed line is for the observed increase of 24% at 150 MeV/nucleon (1.19 GV) (Note that these percentage increases are relative to the 1997 cosmic ray maximum, because ACE measurements do not extend back to 1987.). The two lines intersect at the point $K = 0.26$ and $\eta = 0.83$. We have actually chosen the values of chi-square for our contours so that the center one passes through this point and then drawn the other two arbitrarily to indicate the sensitivity of our analysis to the details of the assumed spectral change. Since, in principle, the two iron lines could intersect anywhere in the plane, it is quite gratifying to see that they actually intersect in our allowed region. However, due to the elongated shape of the allowed regions for the neutron monitor analysis, the neutron monitor and spacecraft data are mutually consistent with a simple power law in rigidity dependence of the record increase in cosmic ray fluxes. We note that the recently published results from Payload for Antimatter-Matter Exploration and Light-nuclei Astrophysics (PAMELA) [*Adriani et al.*, 2013] do not have sufficient time resolution to allow a direct comparison with these results.

[20] Another long-running source of cosmic ray measurements is the series of balloon flights carried out by the Lebedev Physical Institute [*Stozhkov et al.*, 2009]. From Figure 1 of *Bazilevskaya et al.* [2012], the balloon instrumentation in 2009 recorded an intensity approximately 17% above the 1987 peak. *Bazilevskaya et al.* [2012] report the "main response" of the balloon instrumentation is about 2.5 GV. From equation (1) with $K = 0.26$ and $\eta = 0.83$, the expected relative increase $\Delta j/j$ at 2.5 GV is 12%, which agrees reasonably well with the balloon observations.

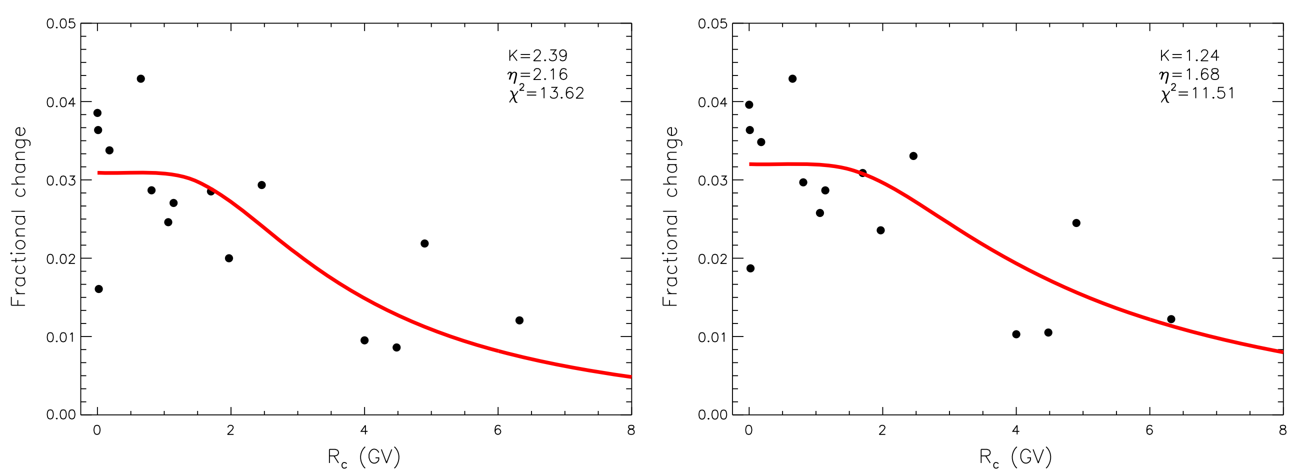


Figure 5. Comparison between the calculation and observation of fractional changes. (Left) Excess at Bartels rotation 2404. (Right) Excess at the time of maximum increase for each station.

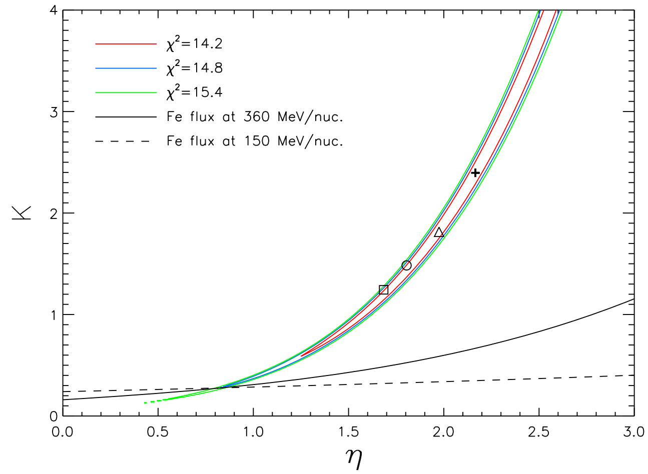


Figure 6. Characteristics of the excess flux at the 2009 cosmic ray maximum. Data on the iron flux are from *Mewaldt et al*. [2010]. The intersection of the various curves at $K = 0.26$ and $\eta = 0.83$ represents our overall best choice for the spectrum of the 2009 maximum. See text for details.

4. Conclusion

[21] From records of 15 neutron monitors, we conclude that neutron count rates on Earth's surface reached a new Space Age record in 2009. To reach a consistent picture of the neutron monitor records, we found it necessary to detrend individual neutron monitor rates for long-term changes in instrument response amounting to typically 2% over the period 1964 to 2009. Although 2% may seem small in absolute terms, it is significant in terms of neutron monitor count rates, some of which vary by almost 30% over the course of the solar modulation cycle. Currently, we do not understand the source of the long-term changes in instrument response.

[22] After detrending individual monitors, a consistent picture emerges. All 15 neutron monitors in our study reach a new record in 2009 relative to the previous Space Age record in 1987. For high-latitude monitors, the typical increase is 3%. At midlatitudes where the geomagnetic cutoff is higher, the increase is still positive but smaller. Combining our results with lower rigidity spacecraft results, we find complete consistency if the spectrum of the new particles present in 2009 is softer than the 1987 Galactic spectrum by about one power in rigidity.

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